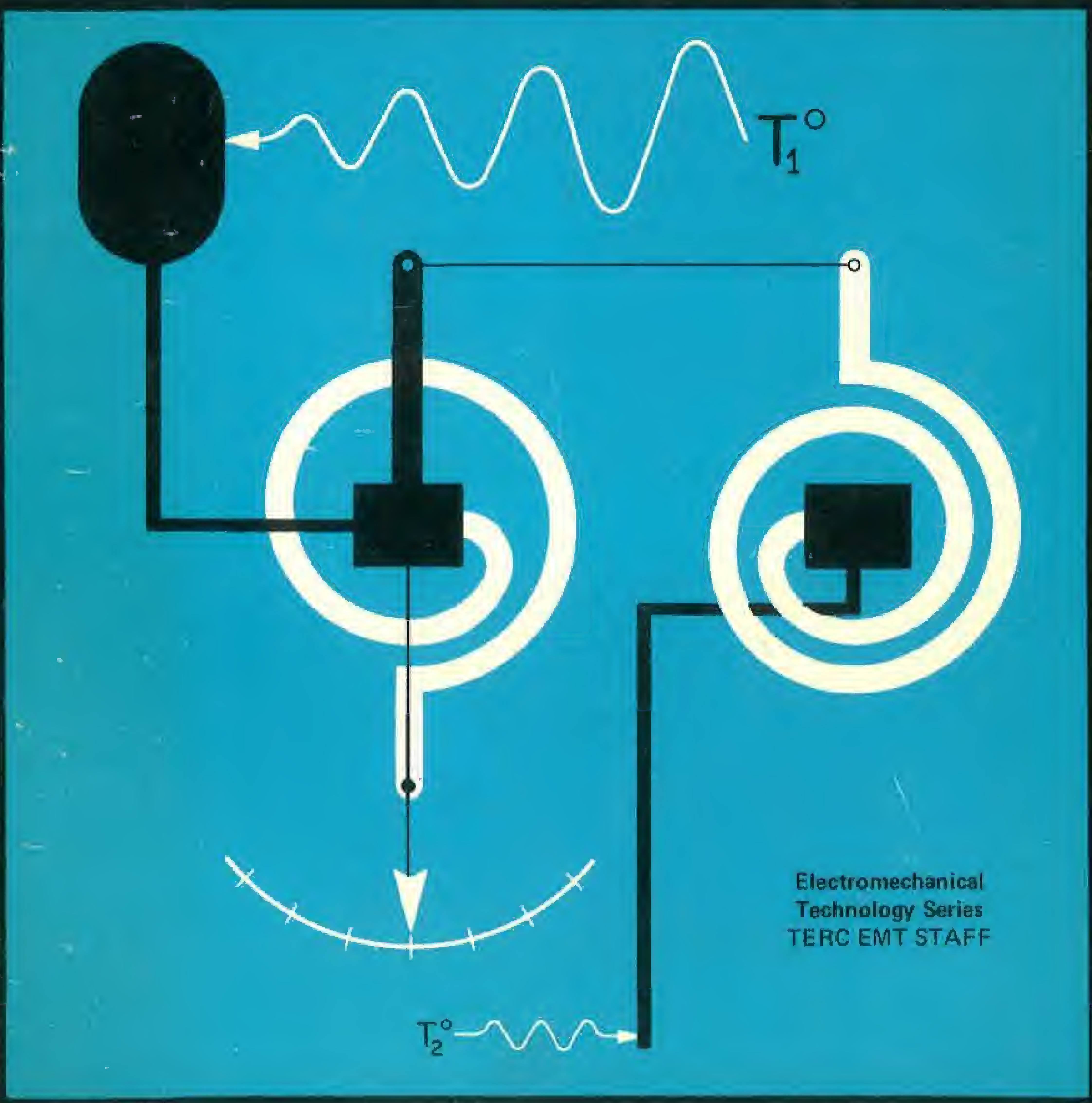
ELECTRO
MECHANISMS

TRANSDUCERS



Electromechanical
Technology Series
TERC EMT STAFF

DELMAR PUBLISHERS, MOUNTAINVIEW AVENUE, ALBANY, NEW YORK 12205

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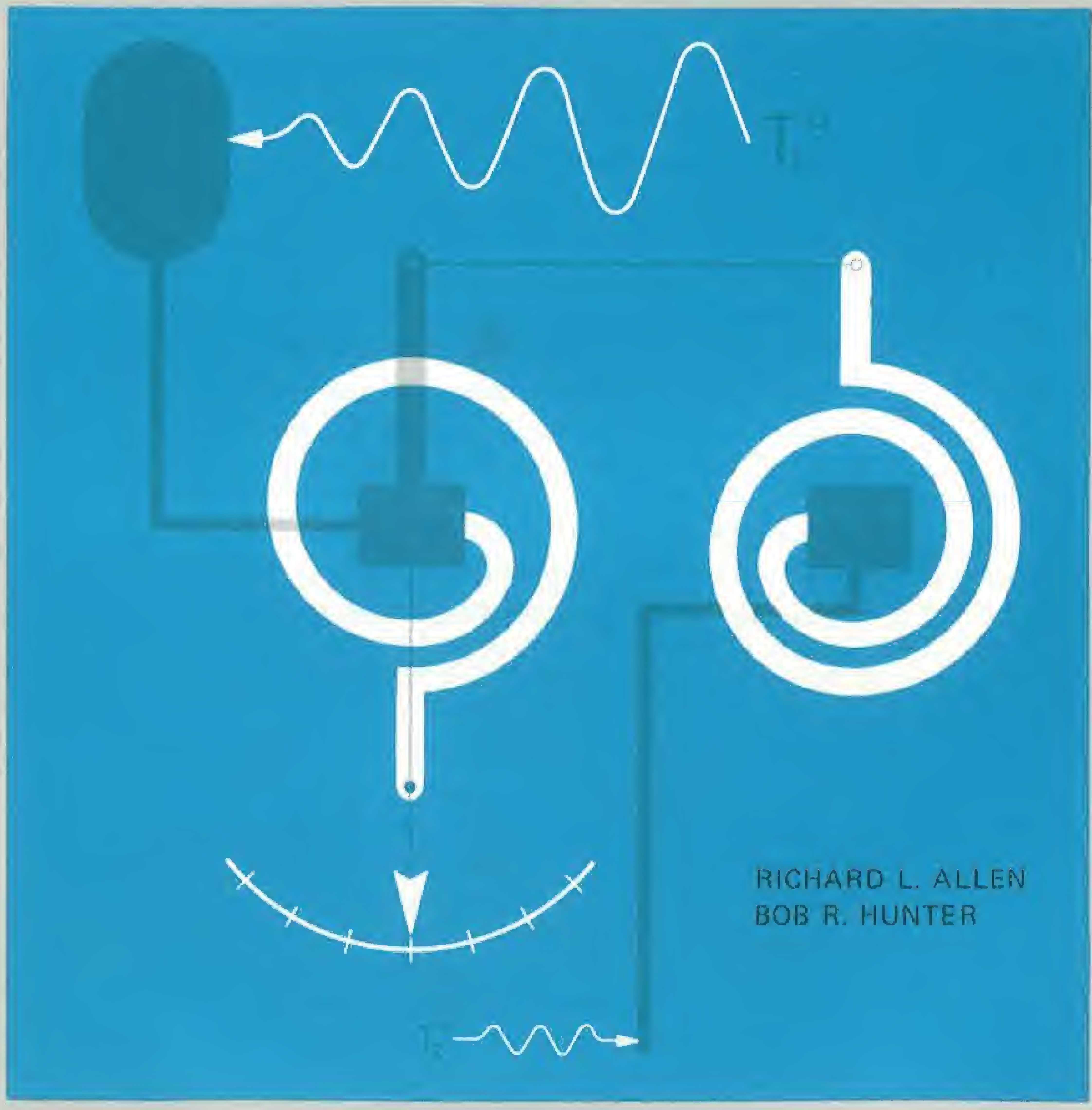

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DELMAR PUBLISHERS

Division of Litton Education Publishing, Inc.

Library of Congress Catalog Card Number:

77-170795

PRINTED IN THE UNITED STATES OF AMERICA

Published simultaneously in Canada by
Delmar Publishers, a division of
Van Nostrand Reinhold, Ltd.

The project presented or reported herein was performed pursuant to a grant from the U.S. Office of Education, Department of Health, Education, and Welfare. The opinions expressed herein, however, do not necessarily reflect the position or policy of the U.S. Office of Education, and no official endorsement by the U.S. Office of Education should be inferred.

Foreword

The marriage of electronics and technology is creating new demands for technical personnel in today's industries. New occupations have emerged with combination skill requirements well beyond the capability of many technical specialists. Increasingly, technicians who work with systems and devices of many kinds – mechanical, hydraulic, pneumatic, thermal, and optical – must be competent also in electronics. This need for combination skills is especially significant for the youngster who is preparing for a career in industrial technology.

This manual is one of a series of closely related publications designed for students who want the broadest possible introduction to technical occupations. The most effective use of these manuals is as combination textbook-laboratory guides for a full-time, post-secondary school study program that provides parallel and concurrent courses in electronics, mechanics, physics, mathematics, technical writing, and electromechanical applications.

A unique feature of the manuals in this series is the close correlation of technical laboratory study with mathematics and physics concepts. Each topic is studied by use of practical examples using modern industrial applications. The reinforcement obtained from multiple applications of the concepts has been shown to be extremely effective, especially for students with widely diverse educational backgrounds. Experience has shown that typical junior college or technical school students can make satisfactory progress in a well-coordinated program using these manuals as the primary instructional material.

School administrators will be interested in the potential of these manuals to support a common first-year core of studies for two-year programs in such fields as: instrumentation, automation, mechanical design, or quality assurance. This form of *technical core* program has the advantage of reducing instructional costs without the corresponding decrease in holding power so frequently found in general core programs.

This manual, along with the others in the series, is the result of six years of research and development by the *Technical Education Research Centers, Inc.,* (TERC), a national nonprofit, public service corporation with headquarters in Cambridge, Massachusetts. It has undergone a number of revisions as a direct result of experience gained with students in technical schools and community colleges throughout the country.

Maurice W. Roney

The Electromechanical Series

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Preface

Technology by its very nature is a laboratory-oriented activity. As such, the laboratory portion of any technology program is vitally important. These materials are intended to provide meaningful experience in basic transducers for students of modern technology.

The topics included provide exposure to: basic principles of measurement as well as pressure, temperature, level, rate, photoelectric, and sound transducers.

The sequence of presentation chosen is by no means inflexible. It is expected that individual instructors may choose to use the materials in other than the given sequence.

The particular topics chosen for inclusion in this volume were selected primarily for convenience and economy of materials. Some instructors may wish to omit some of the exercises or to supplement some of them to better meet their local needs.

The materials are presented in an action-oriented format combining many of the features normally found in a textbook with those usually associated with a laboratory manual. Each experiment contains:

1. An INTRODUCTION which identifies the topic to be examined and often includes a rationale for doing the exercise.
2. A DISCUSSION which presents the background, theory, or techniques needed to carry out the exercise.
3. A MATERIALS list which identifies all of the items needed in the laboratory experiment. (Items usually supplied by the student such as pencil and paper are normally not included in the lists.)
4. A PROCEDURE which presents step-by-step instructions for performing the experiment. In most instances the measurements are done before calculations so that all of the students can at least finish making the measurements before the laboratory period ends.
5. An ANALYSIS GUIDE which offers suggestions as to how the student might approach interpretation of the data in order to draw conclusions from it.
6. PROBLEMS are included for the purpose of reviewing and reinforcing the points covered in the exercise. The problems may be of the numerical solution type or simply questions about the exercise.

Students should be encouraged to study the text material, perform the experiment, work the review problems, and submit a technical report on each topic. Following this pattern, the student can acquire an understanding of, and skill with, basic transducers that will be extremely valuable on the job. For best results, these students should have a sound background in technical mathematics (algebra, trigonometry, and introductory calculus.)

These materials on basic transducers comprise one of a series of volumes prepared for technical students by the TERC EMT staff at Oklahoma State University, under the direction of D.S. Phillips and R.W. Tinnell. The principal authors of these materials were Bob R. Hunter and Richard L. Allen.

An *Instructor's Data Book* is available for use with this volume. Mr. Richard L. Allen was responsible for testing the materials and compiling the instructor's data book for them. Other members of the TERC staff made valuable contributions in the form of criticisms, corrections, and suggestions.

It is sincerely hoped that this volume as well as the other volumes in this series, the instructor's data books, and other supplementary materials will make the study of technology interesting and rewarding for both students and teachers.

THE TERC EMT STAFF

Contents

experiment 1 MATERIAL BEHAVIOR

INTRODUCTION. Control and instrumentation mechanisms play an important role in the highly technical world of today. In this experiment we will examine the behavior of some materials that affect control in mechanisms.

DISCUSSION. You should already know that most materials are affected by varying environmental conditions. For instance, steel is affected by temperature, stress, and strain. The resistance and the length of copper is affected by temperature. The length of wood and hair are affected by humidity. The conductivity of salt is affected by moisture. We use such knowledge in the design of control equipment. This equipment will investigate the effects of temperature, elongation, humidity, conductivity and hysteresis.

In stating his law of constant proportionality, Georg Simon Ohm had to add the provision that the temperature in the environment must be kept constant. As he found out, temperature does affect the resistance of a wire.

The resistance of a wire changes in two ways due to heat. One way is due to the temperature only, and the other way is due to the deformation of the wire when heat is applied.

The resistance of any electric conductor at room temperature with constant length is given by

$$\boxed{R = \rho \times \frac{\ell}{d^2}} \tag{1.1}$$

where R is the resistance of the conductor in ohms, ℓ is the length of the conductor in feet, d^2 is the cross-sectional area of the conductor in circular mills, and ρ is the specific resistance of the material in ohms per mil-foot at 20° C. For copper at room temperature, ρ is equal to 10.37 ohms per mil-foot. As an example, let's find the resistance of 500 feet of copper wire having a diameter of 20 mils at a temperature of 20°C. Since d = 20 mils, d^2 = 400 circular mils, then

$$R = \rho \frac{\ell}{d^2} = 10.37 \times \frac{500}{400} = 13.0 \text{ ohms}$$

This example is correct only when the temperature of the environment is 20°C. For calculating the resistance of a conductor of constant length for any temperature, the following equation must be used:

$$\boxed{R = \rho \frac{\ell}{d^2} (1 + \alpha \, \Delta T) \text{ ohms}} \tag{1.2}$$

where $\rho \frac{\ell}{d^2}$ is the resistance at 20°C, α is the temperature coefficient (ohmic change per degree per ohm at 20°C), and ΔT is the difference between the operating temperature and 20°C. For copper, α is equal to 0.00393. Using this relationship, let's calculate the resistance of 1000 feet of #20 AWG copper wire at 40°C.

ρ = 10.37

d = 32 (from an AWG table)

α = .00393

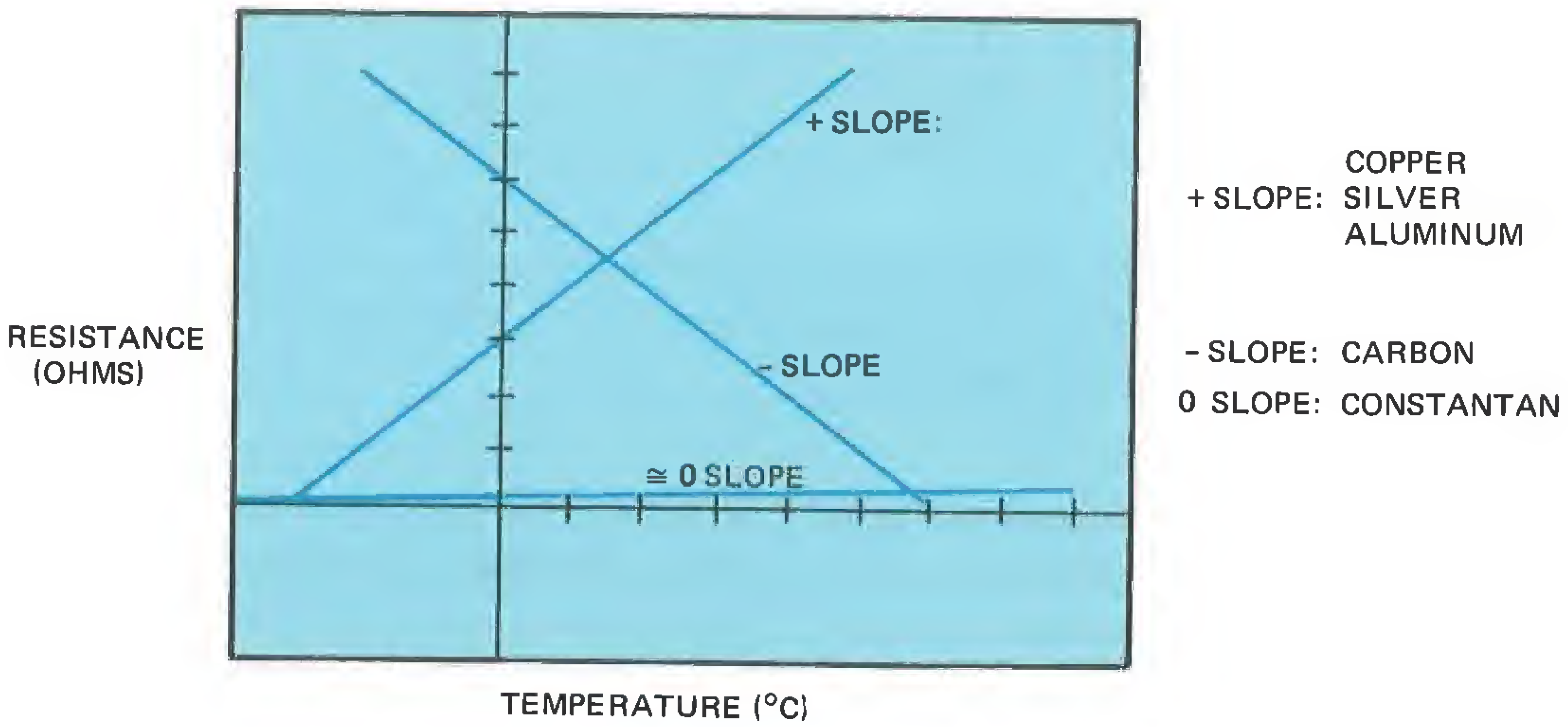


Fig. 1-1 Typical Temperature-Resistance Curves

$$R = \rho \frac{\ell}{d^2} (1 + \alpha \Delta T)$$

$$= \frac{10.37 \times 1000}{32 \times 32} (1 + .00393 \times 20)$$

$$R = 10.9 \text{ ohms}$$

The reason that the resistance of a metal conductor changes when heat is applied is because the heat *agitates* the electrons, creating movement of electrons, which influences the resistance.

For most conducting materials, the resistance increases linearly with an increase in temperature over normal temperature ranges. Some alloys have been developed which do not increase very much at all with an increase in temperature. The slope of a temperature-resistance curve for constantan, for example, is almost flat. Temperature has very little effect on the resistance of this type of material.

There are a few materials that have a negative temperature-resistance characteristic; that is, the resistance decreases as the temperature increases. Carbon is one example. Figure 1-1 shows typical temperature-resistance curves with positive, negative and near zero slopes.

Each individual material has its own characteristic slope and you should not be confused by figure 1-1 into thinking that these materials have the exact slopes shown. The slope of the temperature-resistance curve for each material depends on the temperature coefficient (α) of that material. A table giving the value of α for a variety of materials can be found in most electrical-electronics handbooks.

Some materials with high temperature characteristics are used in temperature-measuring devices. These materials often exhibit nonlinear resistance characteristics and are known by names like sensitors or *thermistors.*

The resistance of a wire also changes with change in length. The change in length can be brought about through effects of temperature, or by stretching.

The resistance of a metallic electrical conductor is directly proportional to its length. If electrons were to flow through two wires, one being twice the length of the other, the electrons flowing in the longer wire would have twice the opportunities to collide with atoms of the conductor material. Therefore, the opposition to electron flow would be double that of the shorter wire.

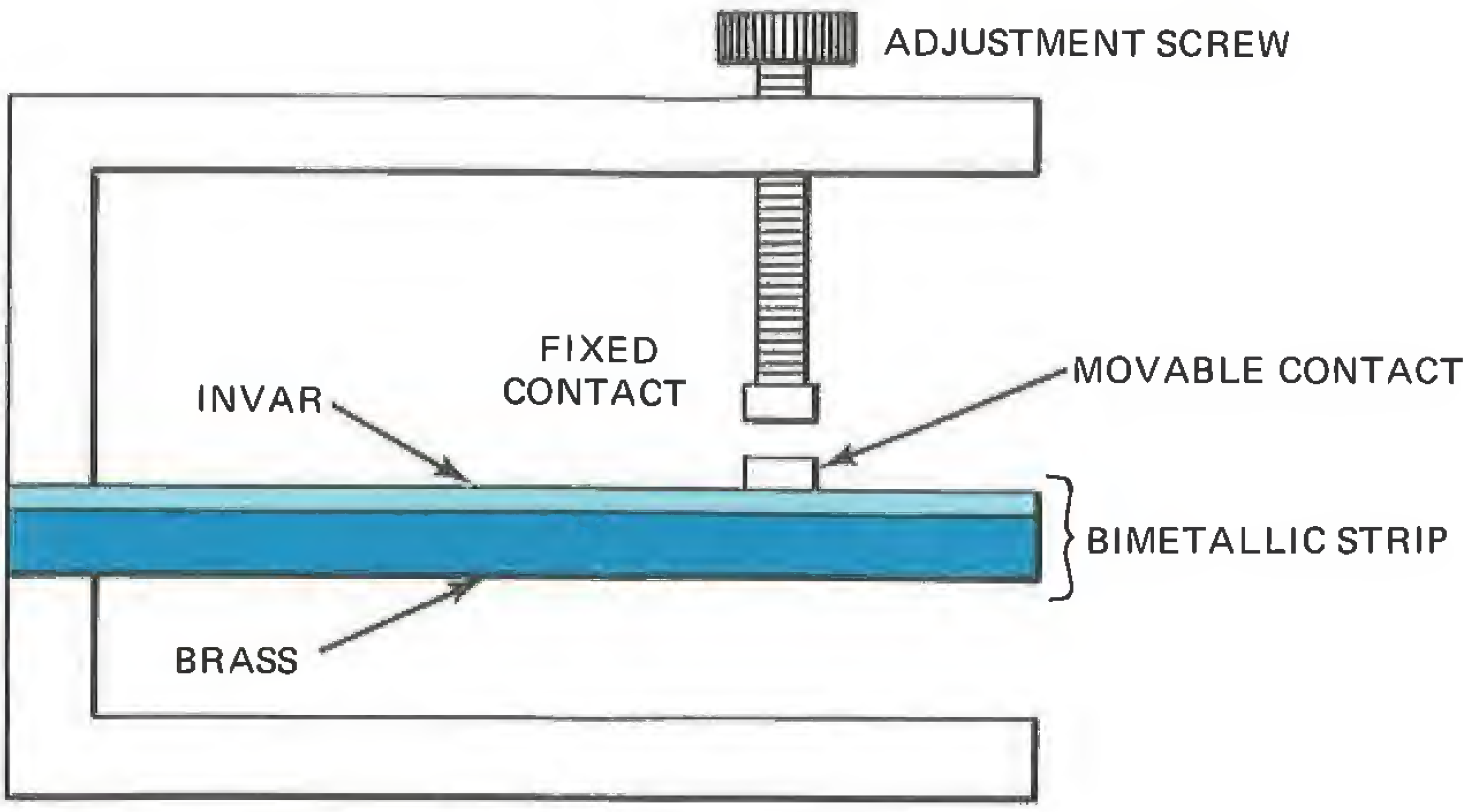


Fig. 1-2 A Typical Thermostat Using a Bimetallic Strip

The *coefficient of linear expansion* is a term used when dealing with materials whose length changes due to temperature changes, stretching due to strain, etc. The coefficient of linear expansion, C, is defined as the change in length, of each unit length, for a rise of temperature of one degree. The change in length is expressed by

$$\boxed{\Delta L = CL_o \Delta T}$$

where

ΔL = Change in length

C = Coefficient of linear expansion

L_o = Original length

ΔT = Temperature change

The most common example of temperature affecting the length of an object is the mercury tube thermometer. It is well known that a mercury tube thermometer is a good indicator of temperature because of its linear expansion when influenced by small temperature changes. When heated, the mercury column expands and rises, and when cooled, the mercury column contracts and returns toward the bottom.

Another example of a control device utilizing expansion due to heat is the thermostat. The temperature-sensitive part of the thermostat is a bimetallic strip consisting of two dissimilar metals welded together. Each material has a different rate of expansion due to heat. Commonly used materials are brass with a high rate of expansion, and invar, an alloy of nickel and iron, which has a relatively low rate of expansion. A thermostat is shown in figure 1-2.

As the bimetallic strip is heated, the greater expansion rate of the brass will cause the free end of the strip to bend upward. When cooled, the strip will return to its original position. The amount the strip bends is directly proportional to the temperature.

The thermostat may be used as an indicating thermometer by attaching a pointer to the free end of the strip and permitting it to move over a calibrated temperature scale. It may also be used to activate the control circuit of some heating or cooling system. When the contacts touch, a circuit is closed which in turn energizes the control mechanism.

Another control device which utilizes the principle of temperature affecting the length of a body is the heater thermostat used

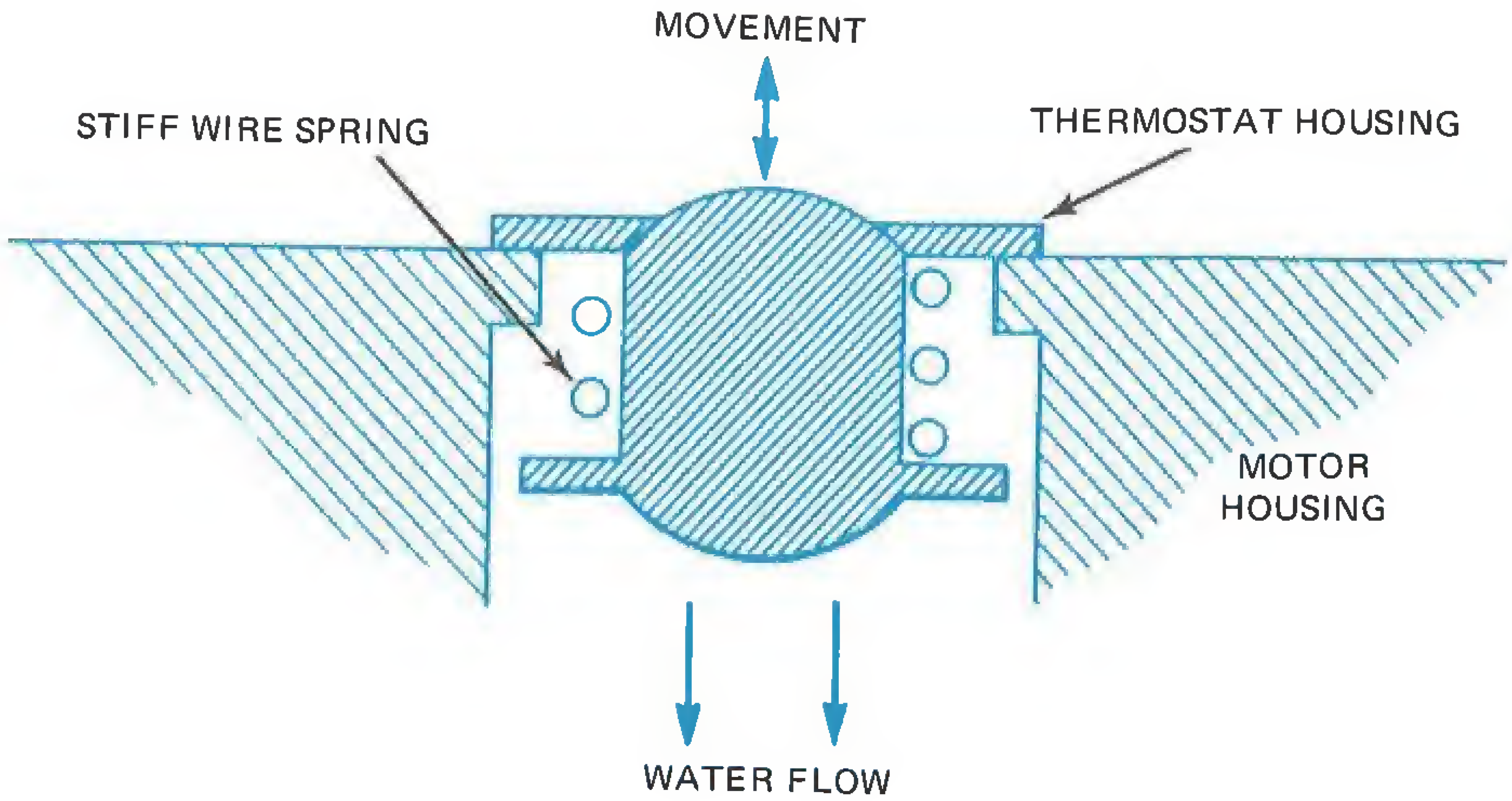


Fig. 1-3 Automobile Thermostat

in the automobile. This device is shown in figure 1-3.

When the water temperature of the automobile is cold, the spring in figure 1-3 is in compression and restricts the water flow path. Since the water circulation is restricted, it gets hotter and hotter as the engine runs. When a preset temperature is reached, the spring begins to expand, pushing the ball-shaped plunger down out of its socket. As the plunger leaves the socket, the water is able to flow more freely through the motor. This thermostat helps keep the engine at a constant temperature, and helps in rapid warming of the heater during the winter months.

The length of a metallic conductor also changes when under stress. Here again the change in length affects the resistance of the conductor.

A good example of a stress-resistance control device is the *strain* gage. A strain gage is a transducer employing electrical resistance variation to sense the strain of a body. It can be used to measure weight, pressure, mechanical force, or displacement. The basic structure is a fine wire looped back and forth on a flexible mounting plate. This plate is bonded to the test piece. As the length of the wire changes due to the strain of the material to which it is bonded, the resistance of the wire changes. The change in resistance is so small, a Wheatstone Bridge is often used to determine the change in resistance accurately. Dummy gages are sometimes employed along side of the strain gage to compensate for temperature and other uncontrollable variables. The dummy gage is connected in a position that is not affected by the test strain. Figure 1-4 shows a typical strain gage circuit.

A table of common materials and their coefficient of linear expansion is given in figure 1-5.

Because there are no absolutely elastic materials, none will return to its exact original shape when the deforming force is removed. This is because the molecular material has internal friciton. Steel, glass, copper, brass, and other materials develop only small internal friction when they are only distorted a small amount. On the other hand, rubber can be

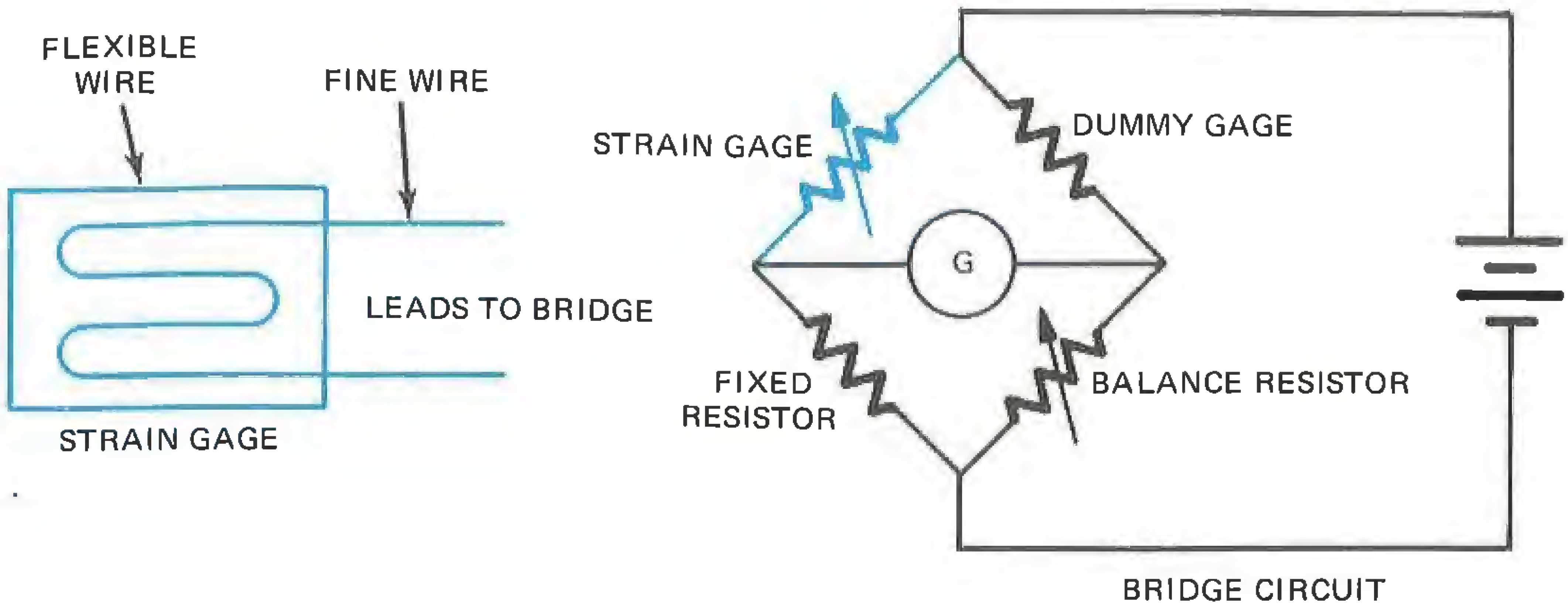


Fig. 1-4 Strain Gage and Bridge Circuit

Substance	Coefficient $\times 10^{-5}/^\circ C$	Coefficient $\times 10^{-5}/^\circ F$
Brass	1.8	1.0
Copper	1.7	0.94
Iron	1.2	0.67
Silver	2.0	1.1
Steel	1.2	0.70

Fig. 1-5 Coefficient of Linear Expansion

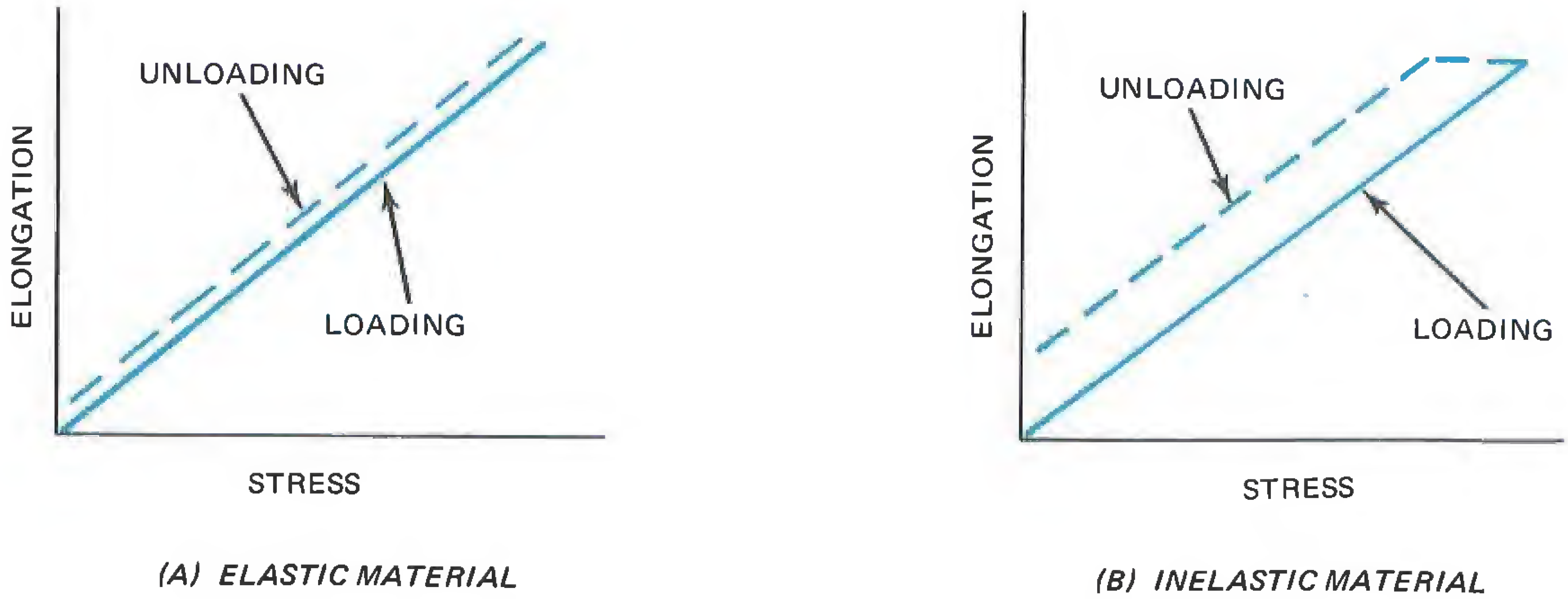
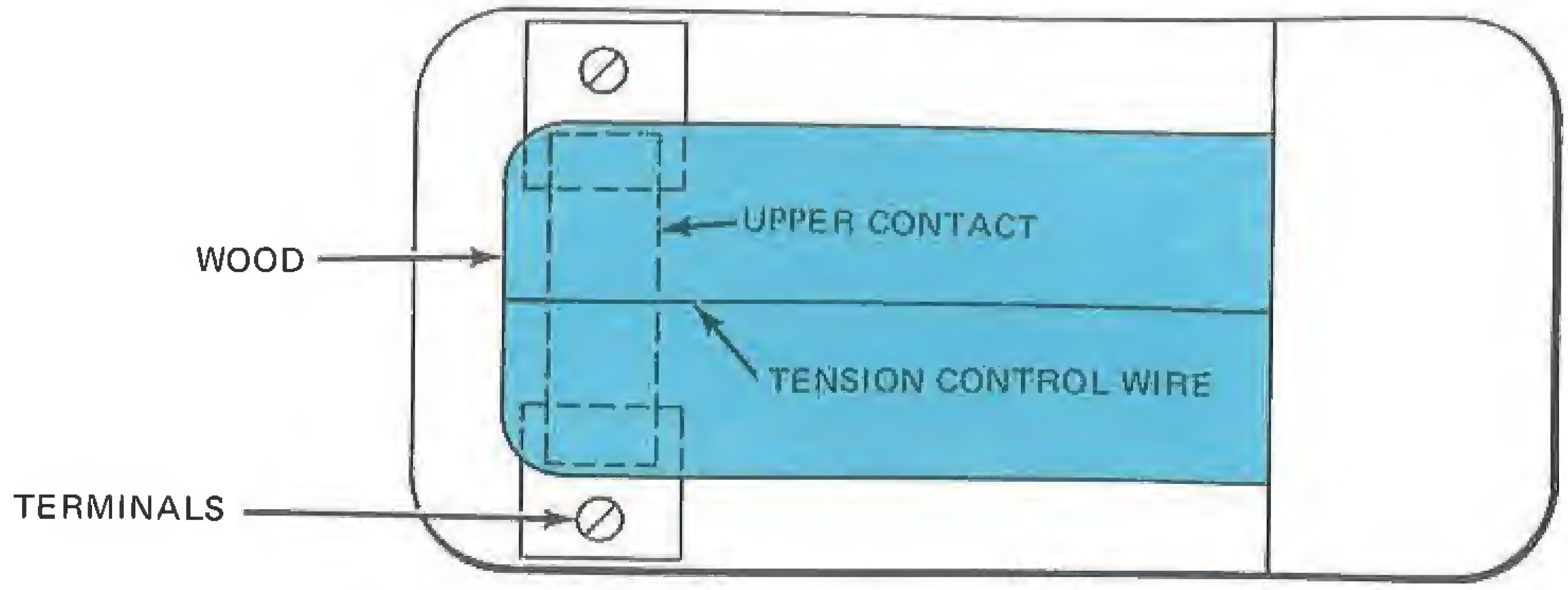
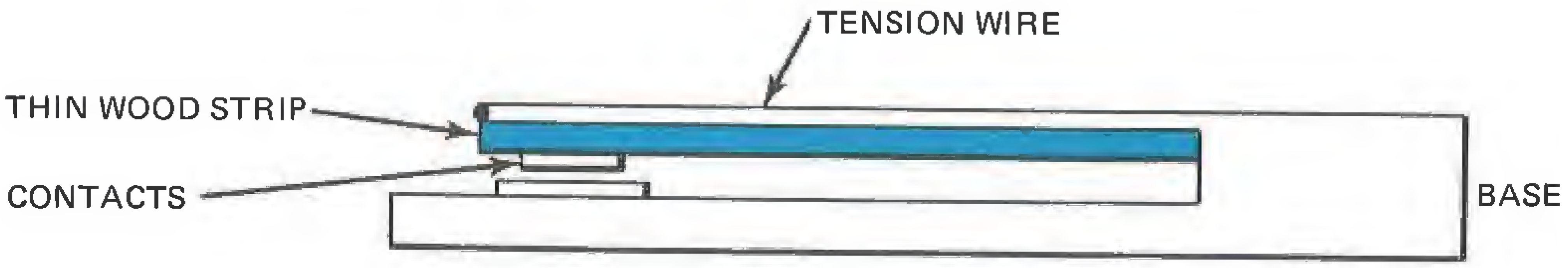


Fig. 1-6 Change in Linear Dimension with Stress

permanently distorted a great deal by loading. Steel, brass, and glass so nearly duplicate their original shape with force changes that we can say that they have a very small hysteresis loss (elastic) while that for rubber is relatively large (inelastic) as shown in figure 1-6.



(A) TOP VIEW



(B) SIDE VIEW

Fig. 1-7 A Humidistat Using Wood as a Controller

The hysteresis loop for a material also represents the amount of energy or work required to cause the material to go through a cycle of pressure or force changes.

Gages made of elastic material are usually quite accurate. If the gage were made of rubber, it would be less accurate because rubber does not readily return to its original shape. Materials used in controls are frequently selected because they have a minimal hysteresis effect.

There are several control mechanisms that may be affected by humidity. Controllers, for instance, may use hair, wood, or some other dry substance to actuate a device. Wood expands when it becomes moist and is, therefore, occasionally used as a switching mechanism for instrument controls. A thin piece of wood is used as a control in the humidistat shown in figure 1-7. As the wood absorbs moisture, it bends upward because the tension control wire is held rigid, and the contacts are broken. Hair is also sometimes used as an actuator in humidity control. The hair contracts as it gets moist, and pulls the contacts open.

One of the newer and most interesting control techniques is the use of salts. Dry salt, such as table salt, will not conduct electricity readily. But when salt becomes moist, a chemical reaction takes place and the electrical current increases. When the salt becomes dry again, the circuit will become almost nonconducting.

This process can be seen in reverse by inserting two electrodes in a beaker of distilled water. When a voltage is applied across the electrodes, an ammeter in the circuit shows no current flow. To get conduction in the distilled water, common table salt is added. As the concentration of salt in the water increases, more electrons flow through the

water and increasing current is indicated on the ammeter.

The nonconduction of electrons through pure water is analogous to the inability of a sound to be transferred through a vacuum. In pure water, there are no free carriers to transport the current from one electrode to the other, just as there is no medium through which the sound can travel in the vacuum. Common drinking water has minerals and impurities such as salt in it. The resistance of such water goes down because of the current carriers in the solution.

Sound must have air or some other substance to support its wave movement. In a vacuum, no air is present; therefore, the sound cannot be transferred. This can be demonstrated by putting a ringing bell under a bell jar and evacuating the jar.

MATERIALS

- 1 30 inch, small diameter copper wire
- 1 Light bulb, 100 watt
- 1 Light bulb socket
- 1 48 inch #32 nichrome wire
- 1 Spring balance
- 2 Test probes, 16/2 rubber-cover
- 1 Remote bulb thermometer (or a thermistor)
- 1 Wheatstone Bridge
- 1 VOM or FEM
- 1 Variable transformer (0-130 VAC 60 Hz)
- 1 250 ml beaker
- Distilled water
- Table salt
- Humidistat, hair-actuated
- Rubber bands
- Small cardboard box
- 2 Test stands and clamps

PROCEDURE

1. Set up the apparatus shown in figure 1-8.

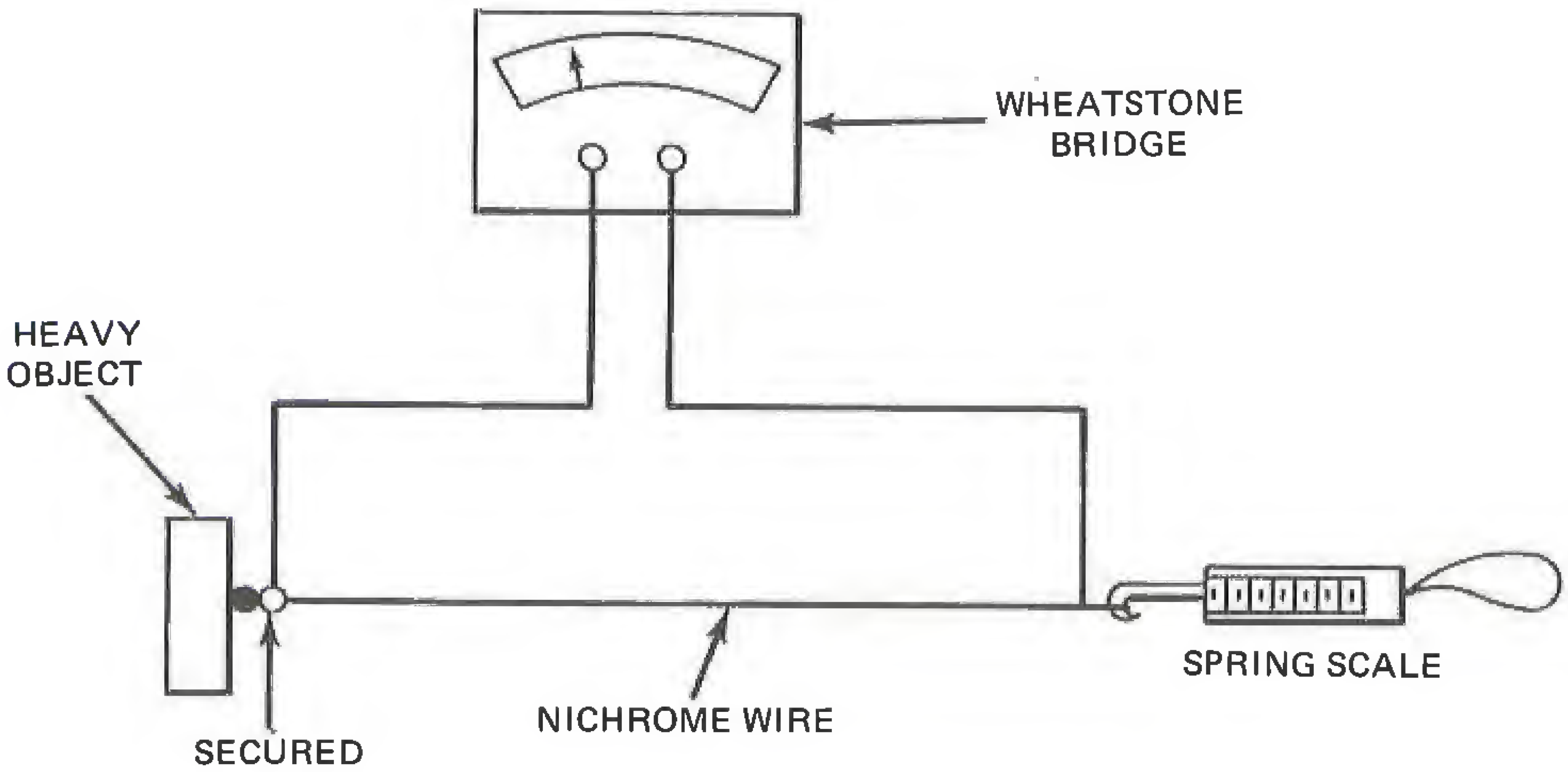


Fig. 1-8 Experimental Setup I

2. Connect the nichrome wire to an object that will not move with 0 – 3 pounds of loading.
3. Load the wire from 24 ounces to 72 ounces in eight-ounce increments. Fill in the Data Table, figure 1-9.

Load (oz)	24	32	40	48	56	64	72
Resistance							

Fig. 1-9 The Data Table

4. Set up the apparatus as shown in figure 1-10.

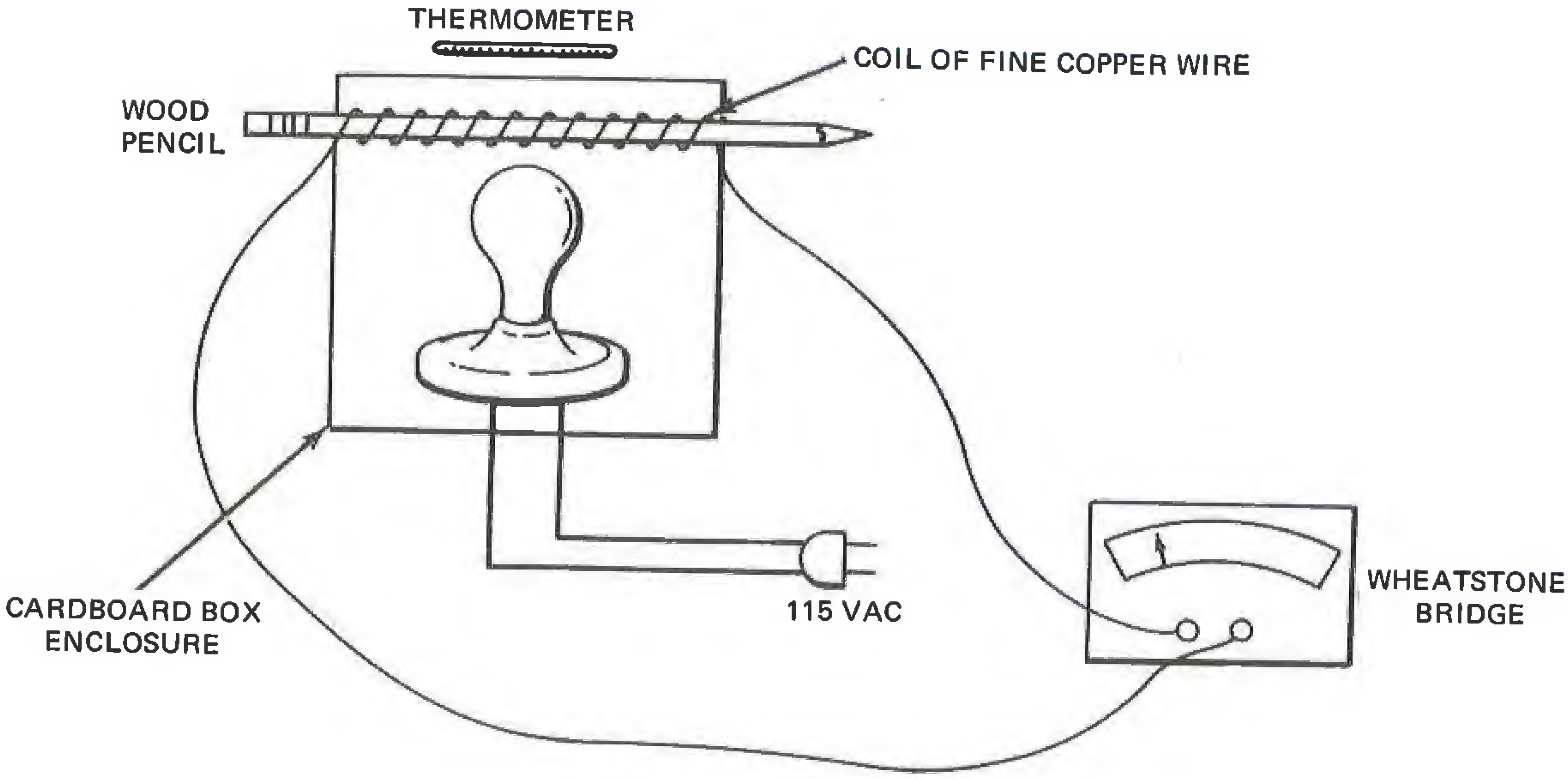


Fig. 1-10 Experimental Setup II

5. Measure the resistance of the wire at room temperature.
6. Turn on the light bulb and record the resistance of the wire at every 5°F change in temperature within the box. Record each value in the Data Table, figure 1-11.

Temp. (°F)	Room Temp	80	85	90	95	100
Resistance						

Fig. 1-11 Temperature-Resistance Table

7. Set up the humidistat apparatus as shown in figure 1-12.
8. Adjust the humidistat so that the contacts are barely closed.
9. Energize the system with 15 volts AC.
10. Add a small drop of water to the strands of hair. Observe the results.

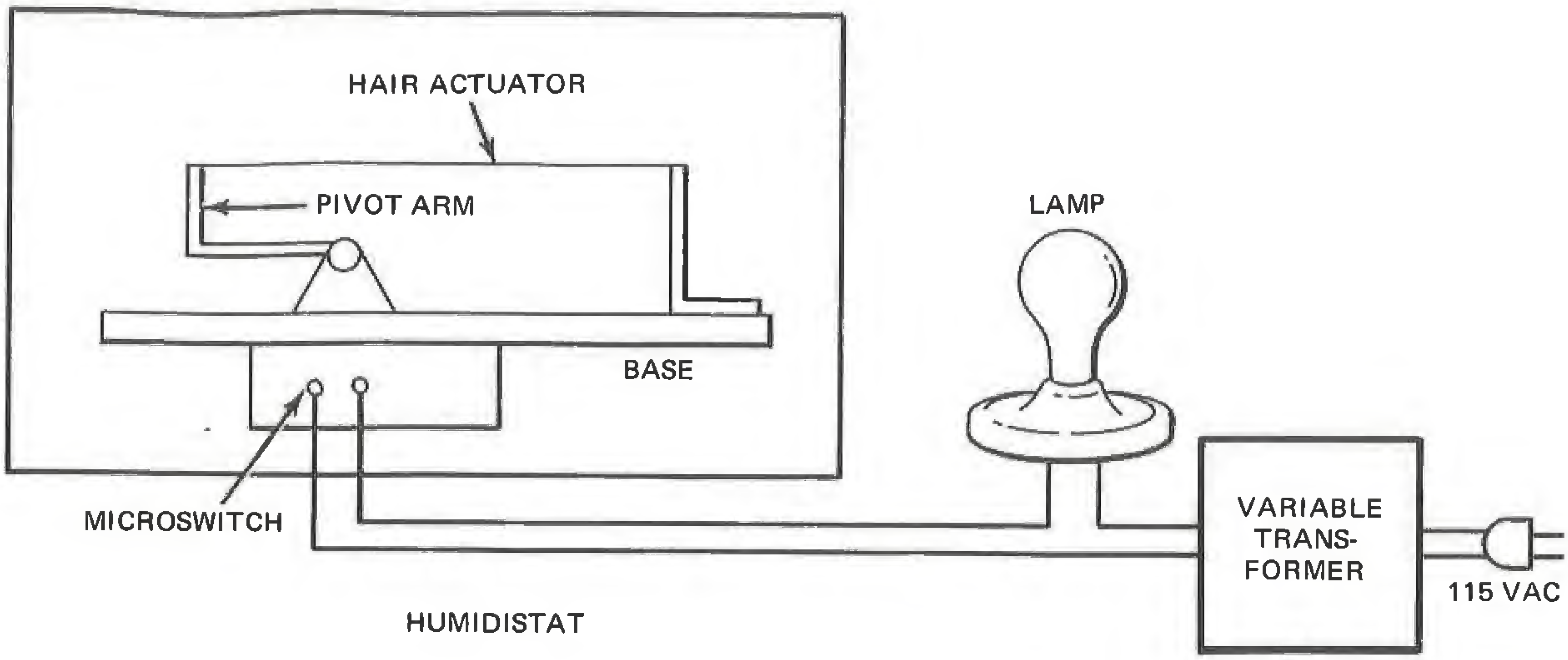


Fig. 1-12 Experimental Set-Up III

11. Distilled water is a nonconductor of electricity. But to be sure, put a small amount in a beaker and insert the probes of an electric circuit in the water as shown in figure 1-13A. If the light does not come on, the water can be assumed to be a nonconductor; add salt to the water and observe the results.
12. Spread a small amount of salt onto the probes as seen in figure 1-13B.
13. Add water to the salt until the light comes on.
14. Observe the reaction of the salt with the water.

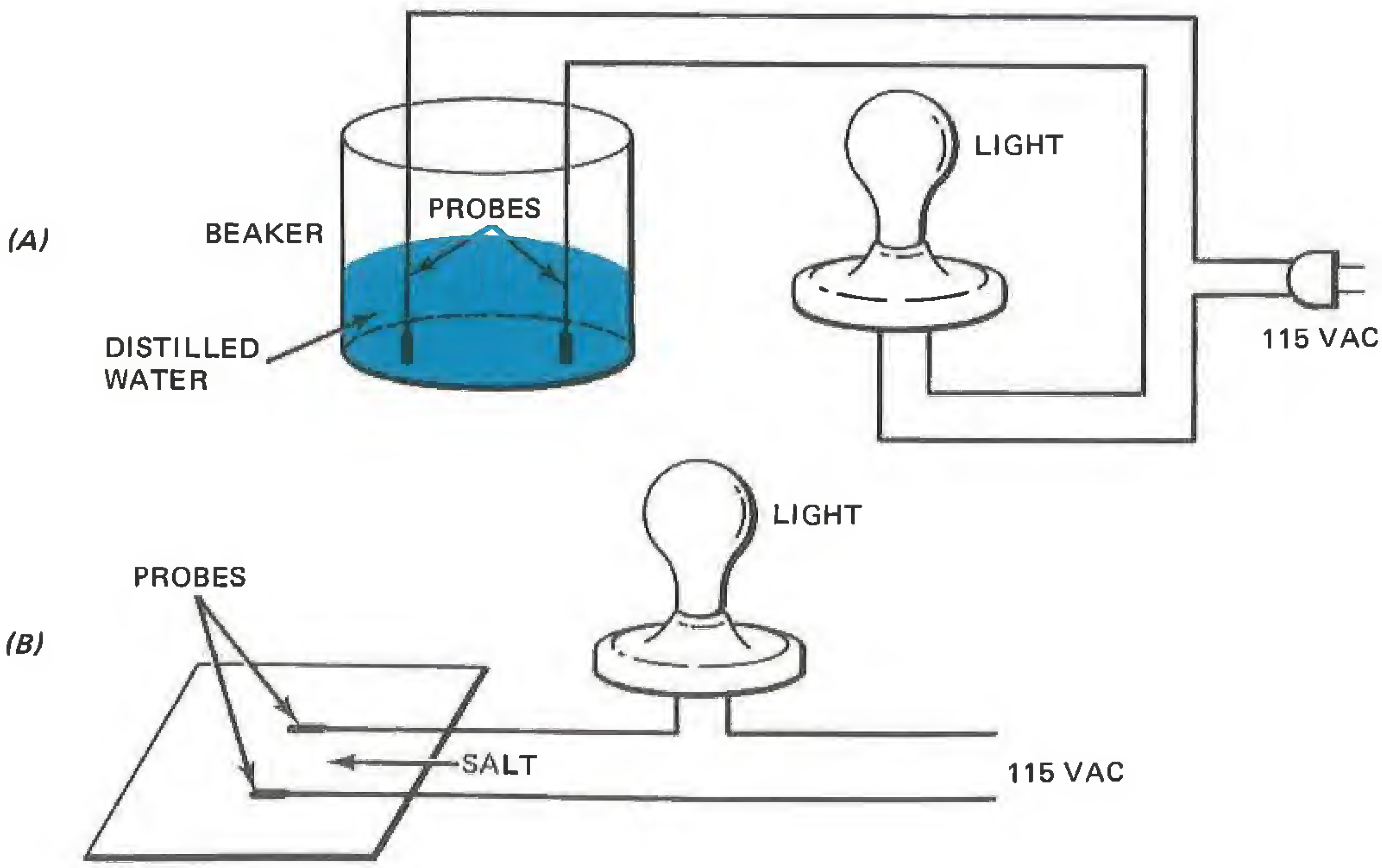


Fig. 1-13 Experimental Setup IV

15. Place a rubber band between two points (unstretched) and measure the distance as shown in figure 1-14.
16. Stretch the band several times for about one minute and remeasure the band length.
17. Determine the length of expansion.

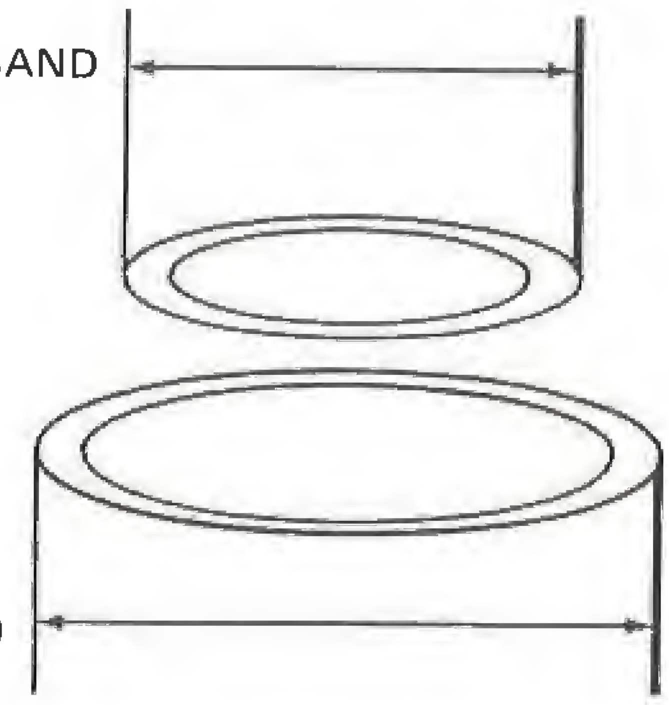


Fig. 1-14 Distortion of a Rubber Band

ANALYSIS GUIDE. Temperature, stress, moisture, and hysteresis are four conditions that affect the materials used in control mechanisms. Explain how these conditions affect the materials they act upon relative to the results of this experiment.

PROBLEMS

1. What is the increase in length of a steel girder that is 50 feet long at 40°F when its temperature rises to 75°F?
2. The lengths of an iron and brass bar are 10.067 inches and 10.110 inches respectively at 110°. At the original temperature of 75°, the length of both is 10 inches. Solve for the coefficient of linear expansion of each.
3. A length of copper telephone line has a resistance of 24 ohms at 20°C. What is the resistance on a hot summer day when the temperature rises to 36°C? ($\alpha = 0.00393$, $\rho = 10.37$.)
4. What length of #22 AWG Nichrome II wire has a resistance of 48 ohms at 200°C? ($\alpha = 0.00016$, d = 25.35 mils, $\rho = 660$.)

experiment 2 *THE THERMOCOUPLE*

INTRODUCTION. Thermocouples play a very important role in industry. They are used as transducers to produce electromotive force to actuate equipment. They are used directly in such devices as furnace valves, recorders, and temperature-recording instruments. In this experiment, we will examine some of the important characteristics of a thermocouple.

DISCUSSION. The simplest electrical temperature-sensitive device is the thermocouple. It consists of a pair of wires of dissimilar metals joined together at one end. The other ends are connected to an appropriate meter or circuit. The joined ends are known as the hot junction and the other ends are the cold ones. When the hot junction is heated, a measurable voltage is generated across the cold ends.

With proper selection of the wires, the voltage varies in relationship to the temperature being measured. Because of this, the thermocouple can be considered a thermoelectric transducer because of its characteristic of converting thermal energy into electrical energy. Figure 2-1 shows a typical circuit using a thermocouple to record temperature changes in a heat chamber.

When the thermocouple is heated at the hot junction, while the cold junction is at a relatively constant temperature, the difference in temperature of the two junctions causes the meter to indicate a current. The indication of the meter is calibrated to be proportional to temperature.

The most common thermocouple materials are combinations of Iron-Constantan, Copper-Constantan, Chromel-Alumel, and Platinum/Rhodium-Platinum. The temperature range for each of these materials is shown in figure 2-2 along with the average output in millivolts per °F.

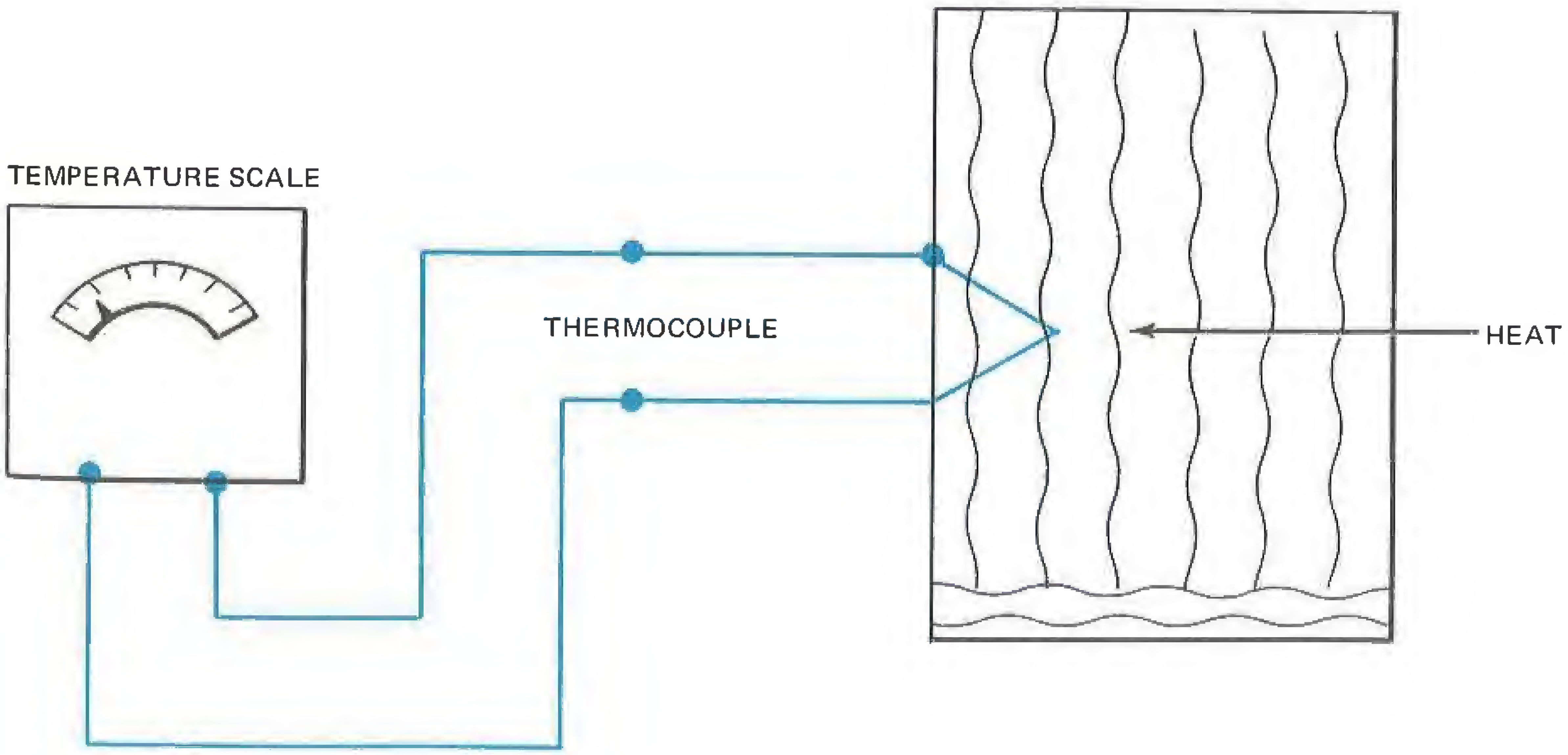


Fig. 2-1 Typical Application of a Thermocouple

Type of Thermocouple	Temp. Range (°F)	Output mV/°F
Iron-Constantan	0° to 1400°	0.03
Chromel-Alumel	500° to 2300°	0.023
Platinum/Rhodium-Platinum	1000° to 2700°	0.005
Copper-Constantan	-300° to +700°	0.025

Fig. 2-2 Table of Thermocouple Characteristics

The name of the material to the *left* of the hyphen in figure 2-2 indicates the *electrically positive* material, and the one to the right indicates the negative material when the thermocouple is subjected to heat.

One meter used with a thermocouple is the millivoltmeter, a permanent-magnet moving-coil instrument that is sensitive to small changes in electrical voltage. A pointer attached to the moving coil indicates the voltage being produced by the thermocouple. The actual meter does not measure temperature changes directly. However, since there is a definite relationship between the temperature of the thermocouple and the voltage produced, the scale can be calibrated in units of temperature. Because these potentials are in millivolts, great care must be exercised in measuring them, because the number of degrees per millivolt may be large, particularly with the platinum alloy thermocouples. An error of one millivolt may establish an error of 50 to 100 degrees.

To measure the output of a thermocouple more accurately than with a millivoltmeter, a *potentiometer* is used. The potentiometer does not use the actual voltage produced by the thermocouple to move a meter mechanism, but compares the thermocouple voltage with a battery-supplied voltage. A simple circuit used is shown in figure 2-3.

When the meter reads zero, the potentials are equal. From figure 2-3 we see that

$$I = \frac{E}{R} = \frac{E_1 - E_2}{R_{meter}}$$

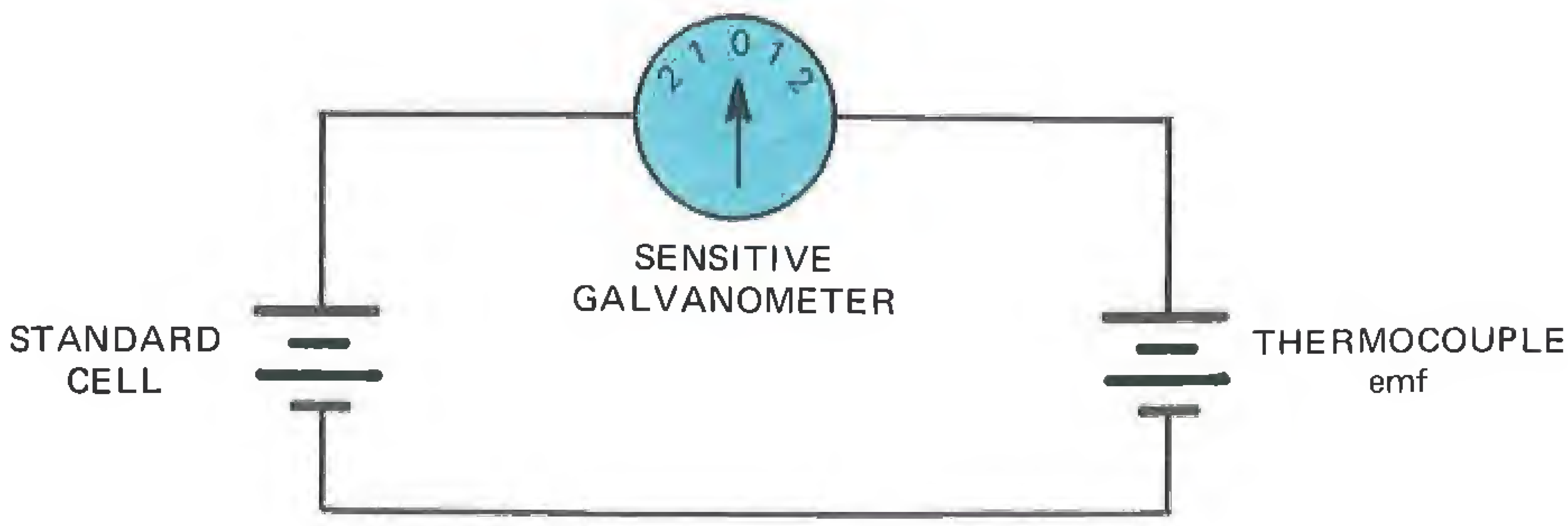


Fig. 2-3 Potentiometer Circuit Comparing Thermocouple Output with a Known Voltage

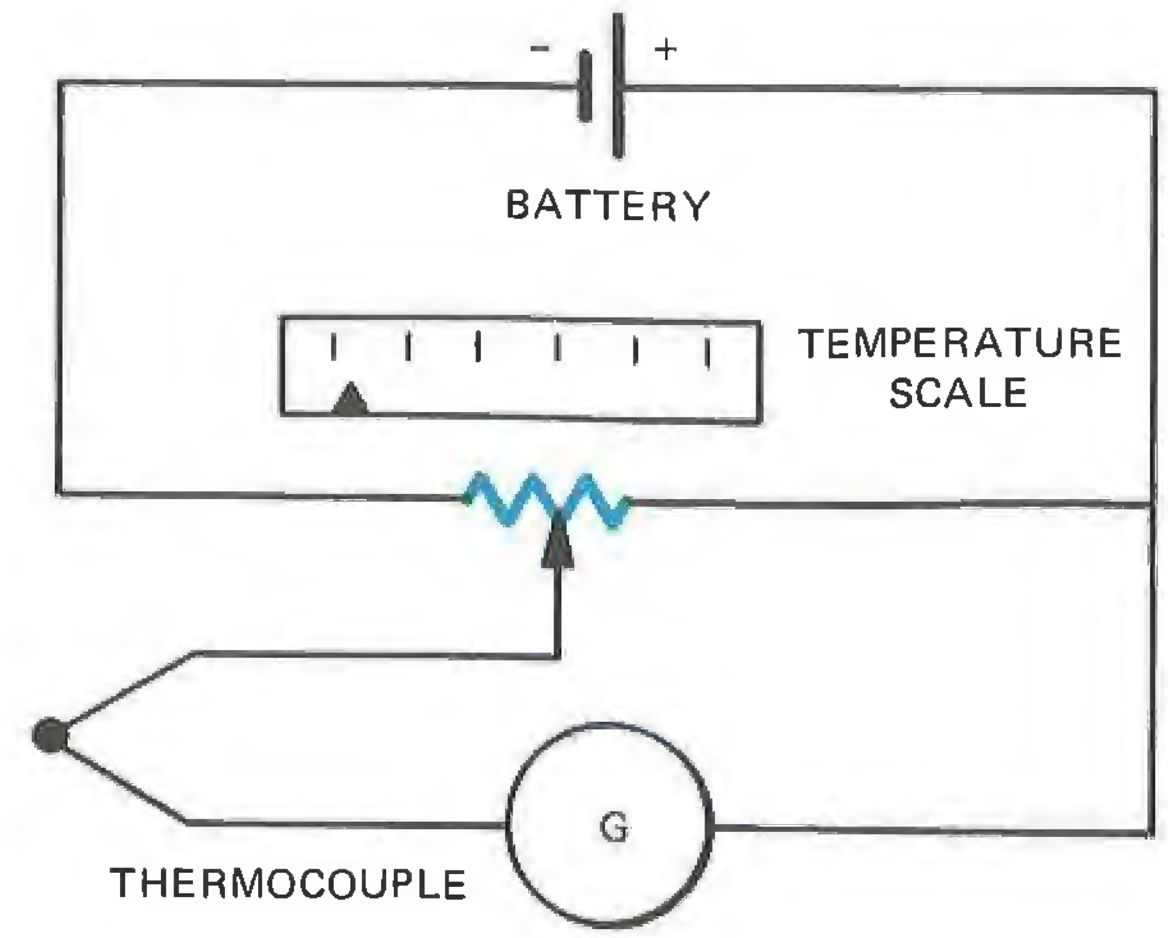


Fig. 2-4 Potentiometer Circuit Used for Measuring Thermocouple Outputs

If I = 0, then $E_1 - E_2 = 0$. This only happens when $E_1 = E_2$. If E_1 is a known value, then when the needle position is at zero, E_2 also becomes known. For calibration readout of the thermocouple voltage, the circuit shown in figure 2-4 can be used.

This circuit is similar to the one in figure 2-3, but it makes use of a slide wire which can be moved to equalize the emf on each side of the meter. Each position of the slide wire corresponds to a temperature reading on a temperature scale.

Three phenomena govern the behavior of a thermocouple: the Seebeck, Peltier, and Thomson Effects.

Thomas Seebeck, a German scientist, was the man who discovered the first thermoelectric device, but he was unaware of it at the time. He twisted the ends of two dissimilar metal wires together so that there were two junctions as shown in figure 2-5.

Simply stated, the Seebeck effect describes the result of heating one junction of two twisted dissimilar metals. The current flow varies with the difference in temperature between the hot junction and the cold junction.

A flow of current is generated by the agitation of electrons when they come in contact with extreme heat. One of the

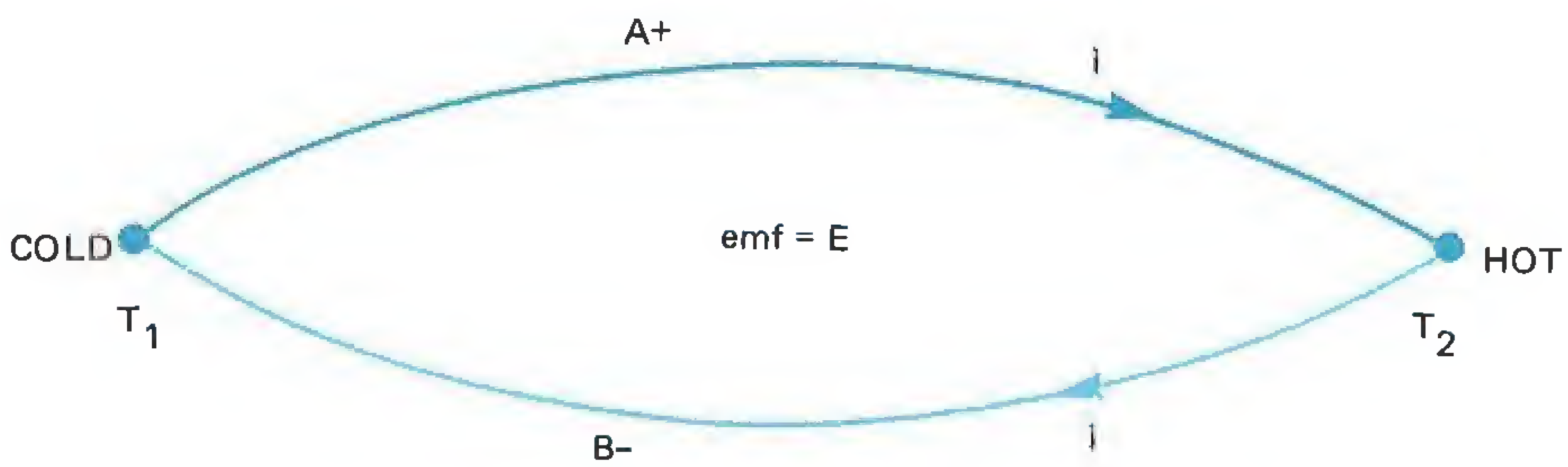


Fig. 2-5 The Seebeck Effect

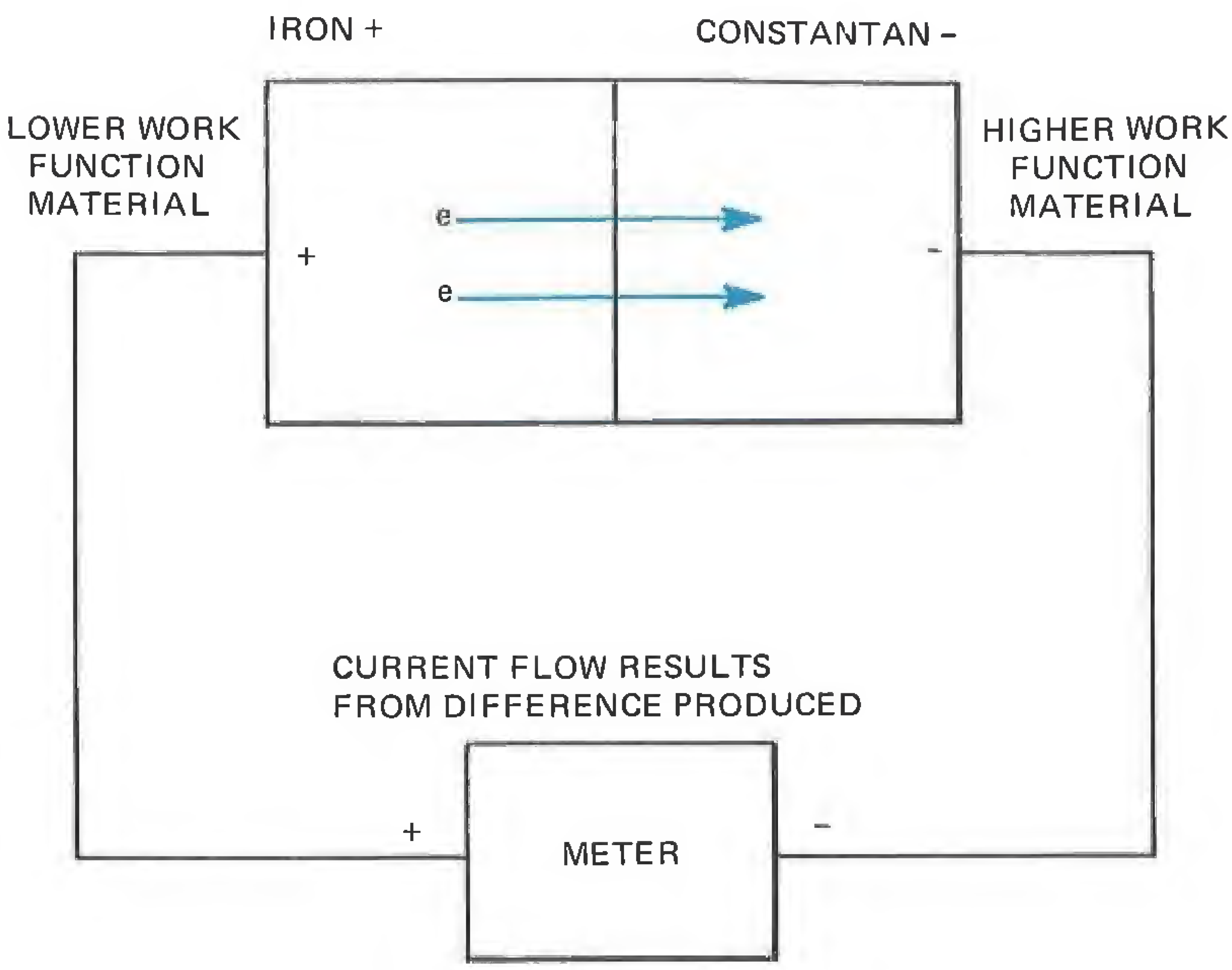


Fig. 2-6 Current Flow Production

materials used will have a lower work function than the other material. The material with the lower work function will give up electrons faster than the other material. Thus, as the temperature rises, electrons are given up from the lower work function material and a positive charge is produced. At a certain temperature level, a certain number of electrons will be emitted and a given current produced. With an increase in temperature, more electrons are emitted and a higher current is produced. Figure 2-6 is a schematic showing how the current is produced.

The current will continue to flow as long as the two junctions are at different temperatures. The emf producing this current is known as the Seebeck thermal emf. The relationship of the emf and the temperature difference $\Delta t = t_2 - t_1$ is shown in figure 2-7.

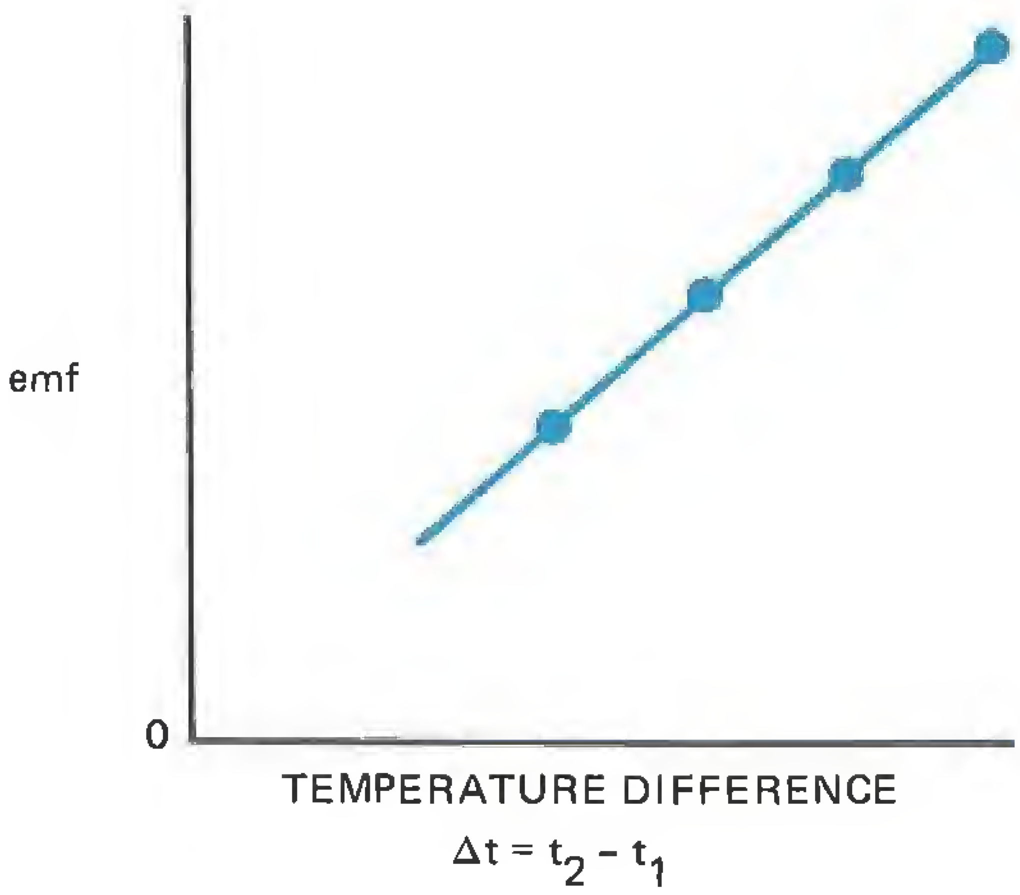


Fig. 2-7 Temperature-emf Relationship in Thermoelectricity

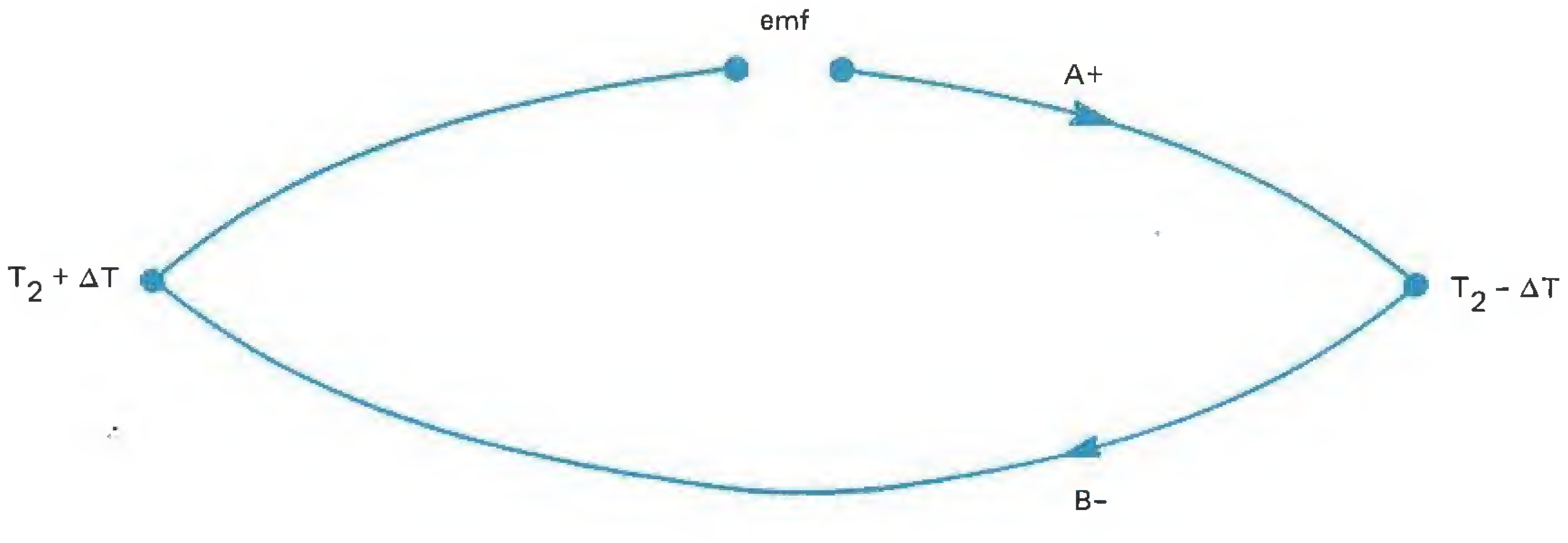


Fig. 2-8 The Peltier Effect

In 1834, Jean C.A. Peltier discovered that when a current flows through the junction of two metals, a rise in temperature was developed at one end and a decrease in temperature was developed at the other end. If the current flows through the junction in one direction, heat is absorbed, but if it flows in the other direction, heat is liberated. The Peltier effect is shown in figure 2-8.

For example, heat is absorbed when a current flows through an iron-constantan hot junction from the constantan to the iron, iron being thermoelectrically positive with respect to constantan. The amount of heat liberated or absorbed when one coulomb of electricity crosses the junction is called the Peltier effect of the temperature at the junction.

When the Seebeck circuit is considered as a reversible heat engine, where the only reversible thermo-effects are the Peltier effects at the junction, the emf produced by the circuit (whose cold junction is kept at a constant temperature) should be directly proportional to the difference between the temperatures of the hot and cold junctions. This, however, does not agree with experimental facts. With a circuit made up of iron and copper wires with the cold junction in melting ice, the emf increases as the temperature of the hot junction is increased, until a maximum is reached. The emf decreases with further rise in temperature, passes through zero, and reverses sign. This reversible temperature effect leads us to the Thomson effect.

The British scientist W.T. Thomson found that an emf could be produced, not only from dissimilar metals, but also from the same metal wire if a temperature difference existed within that particular wire. He found that when a current flows along a copper wire whose temperature varies from point to point, heat is liberated at any point P when the current at P flows in the direction of the heat flow (current flowing from hot junction to cold junction) while heat is absorbed at P when the current flows in the opposite direction. However, in iron, heat is absorbed at P when the current flows in the direction of the flow of heat at P, and heat is liberated when the current flows in the opposite direction. In the copper wire, the current tends to diminish the differences in temperatures, while in the iron wire it tends to increase them.

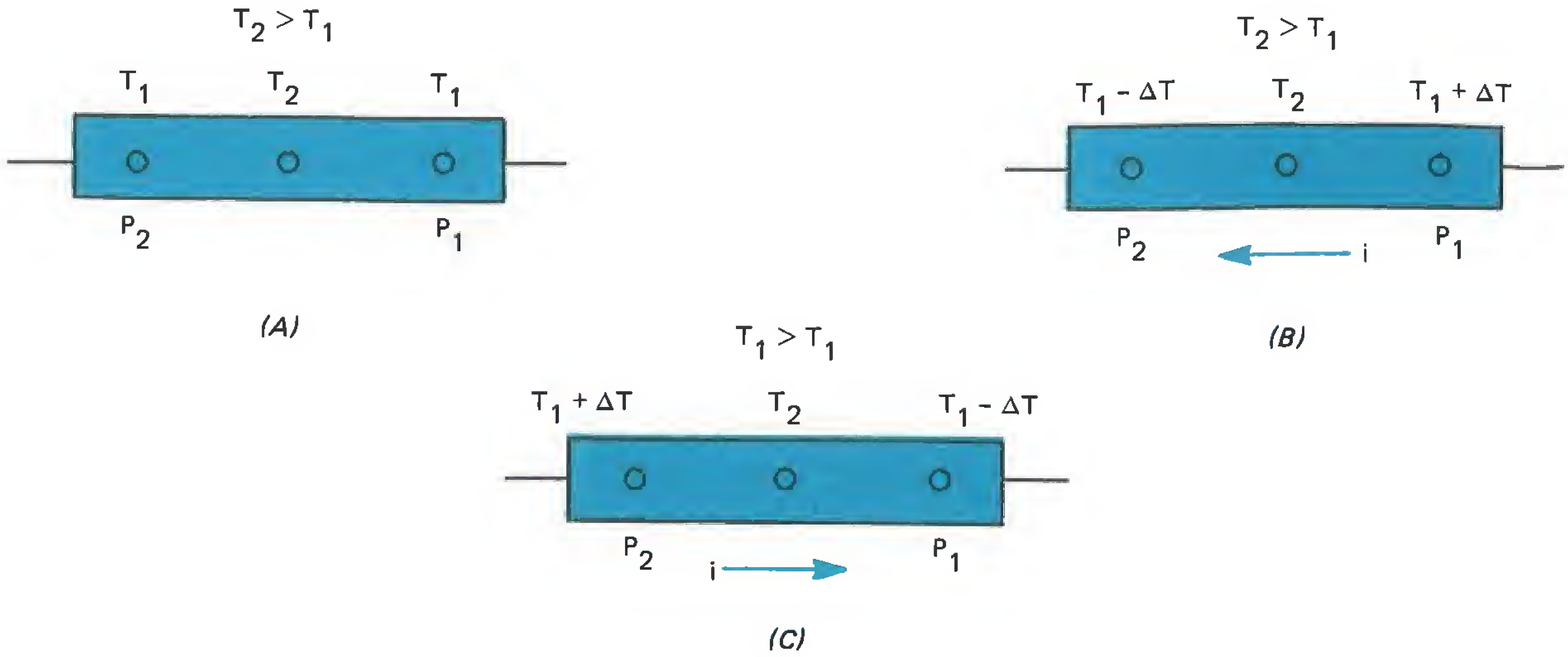


Fig. 2-9 The Thomson Reversible Heat Effect

Figure 2-9 represents a bar of metal which is heated at its midpoint to a temperature T_2. A current from an external source is passed through it. Points P_1 and P_2 which were at equal temperatures T_1 (lower than T_2) when no current was flowing have their temperatures changed to $T_1 + \Delta T$ and $T_1 - \Delta T$ respectively when the current flows in the direction shown in figure 2-9B. When the current flows in the opposite direction, the temperatures reverse to $T_1 + \Delta T$ and $T_1 - \Delta T$ respectively as shown in figure 2-9C. This analogy applies to the behavior of copper.

The Thomson reversible heat effect is different from the Peltier effect in that it occurs in a homogeneous conductor rather than at a junction of two dissimilar conductors.

The voltage which produces the Seebeck current is the sum of the Peltier emf at the junctions and the two Thomson emfs along the dissimilar wires. This is the basis of thermoelectric thermometry. If E is the effective emf of the thermocouple, or the Seebeck voltage, then

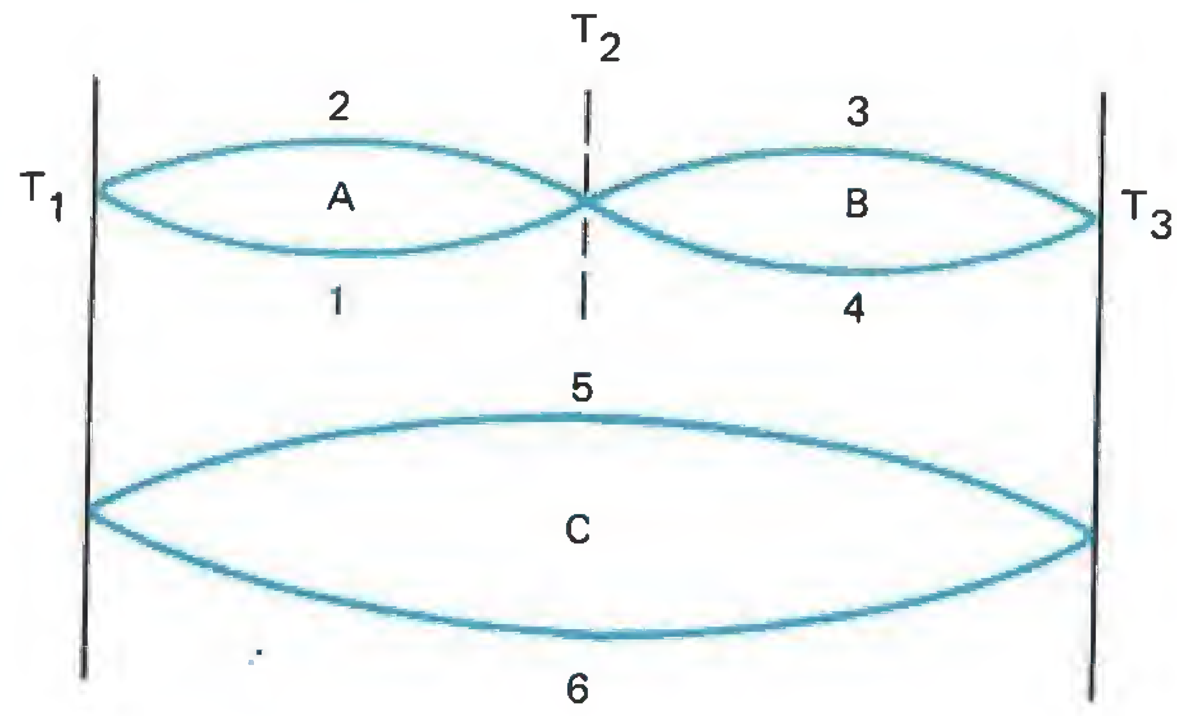
$$\boxed{E = C(T_1 - T_2) + K(T_1^2 - T_2^2)} \qquad \textbf{(2.1)}$$

where C is the Thomson coefficient and K is the thermal conductivity of the metals used.

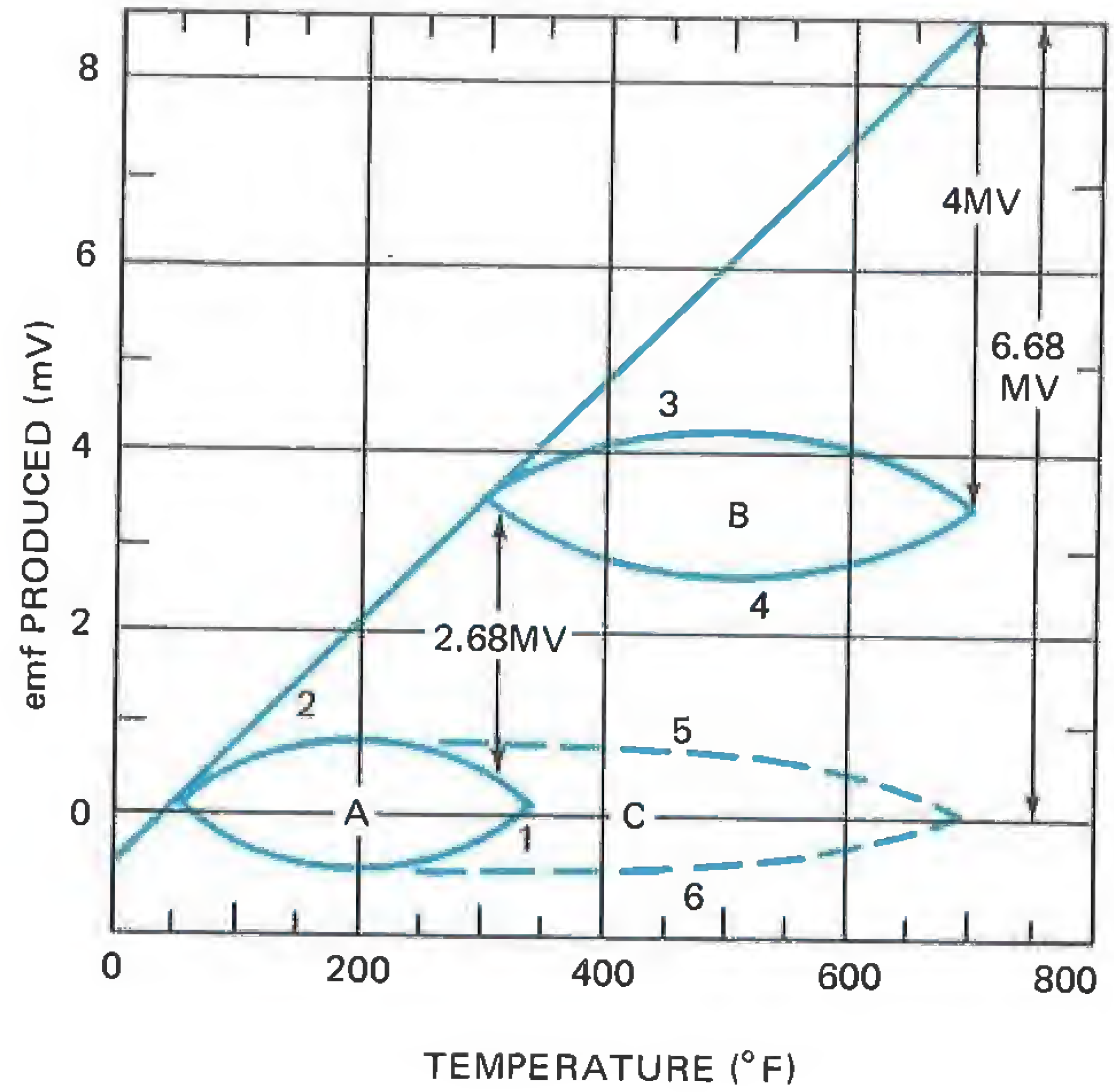
Two laws dealing with thermocouples are worthy of note: The law of intermediate temperatures, and the law of intermediate metals.

The law of intermediate temperatures states that if two dissimilar homogeneous metals produce an emf of E_1 when the junctions are at temperatures T_1 and T_2 and a thermal emf of E_2 when the junctions are at T_2 and T_3, the emf generated when the junctions are at T_1 and T_3 will be $E_1 + E_2$.

In effect this law states that the sum of the emfs produced by two thermocouples — one with its junctions at T_1 and T_2, the other with its junctions at T_2 and T_3 — will be the same as a single thermocouple with its junctions at T_1 and T_3. Figures 2-10A and 2-10B show this relationship.



(A) $emf_C = emf_A + emf_B$

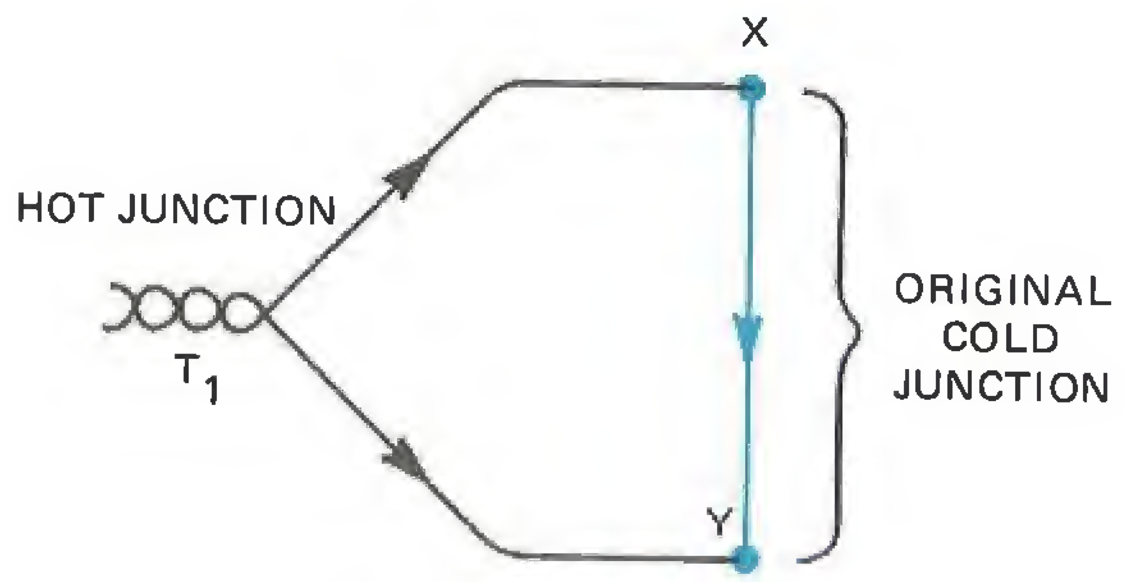


(B)

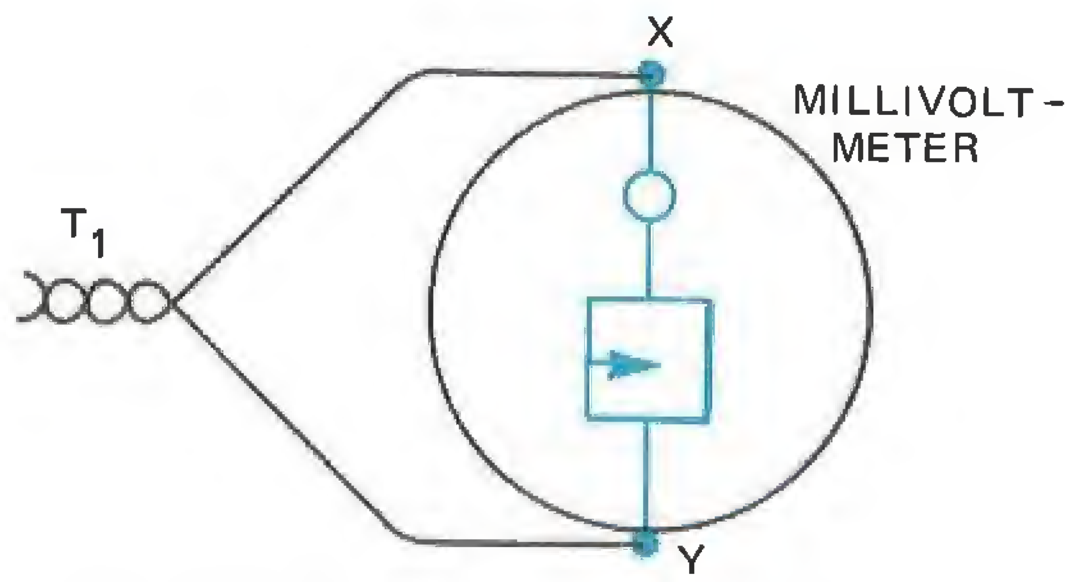
Fig. 2-10 (A) Dividing a Thermocouple into Two Components
(B) Graphical Representation of a Thermocouple with Intermediate Temperature Junctions

The law of intermediate metals states that if a third wire is introduced into the loop circuit of a thermocouple at the original cold junction, see figure 2-11A, the emf will remain unchanged provided the new junctions formed, X and Y, remain at the same temperature. Practically speaking, this law is very important because it means that, provided the equipment used for measuring the emf is maintained at the same temperature, the presence of other junctions of different metallic compositions will not influence the total emf of the circuit. Actually the millivoltmeter can be inserted to measure the emf as shown in figure 2-11B.

There are a number of uses of the thermocouple. One of the more widely used applications is the control mechanism on the gas furnace. The thermocouple is used here



(A) ADDITIONAL OF A THIRD WIRE XY



(B) ADDITION OF A MILLIVOLTMETER

Fig. 2-11 Illustration of the Law of Intermediate Metals

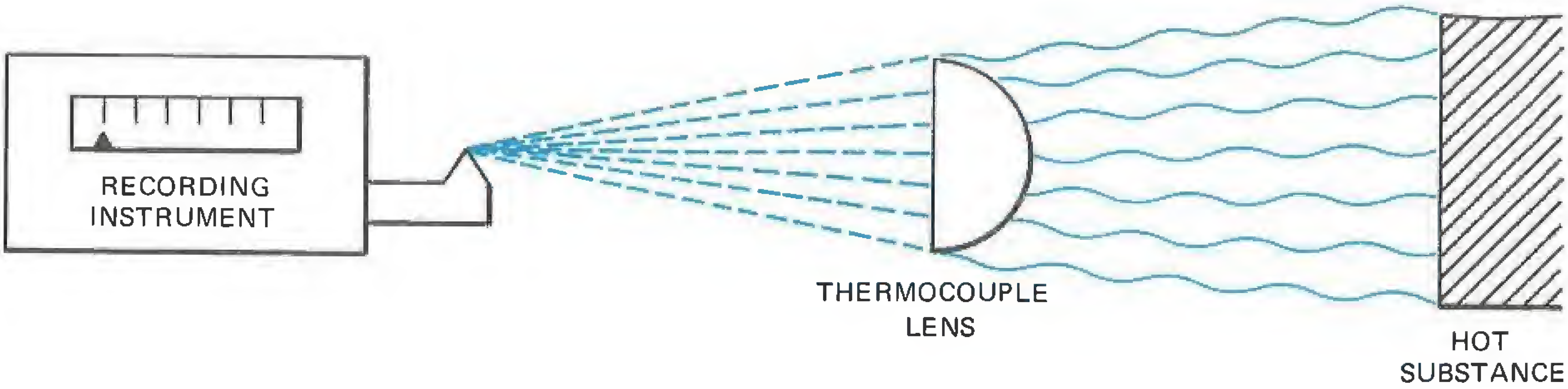


Fig. 2-12 The Radiation Pyrometer

as a safety control for the gas valve. A similar function is the gas valve on the water heater. The thermocouple also has many uses in temperature-indicating and recording instruments. Examples include the pyrometer, potentiometer, and mechanical clutch. To show one application of the thermocouple, radiation pyrometer will be discussed. Many special thermometers are required for high temperature industrial processes. The high temperatures involved can not be measured by a mercury thermometer because the glass would melt and the mercury would boil away. What is needed is an instrument which does not make direct contact with the substance whose temperature is to be determined. The instrument used is known as a pyrometer. There are two types; the radiation pyrometer and the optical pyrometer. The optical pyrometer does not make use of the thermocouple but the radiation pyrometer does. Figure 2-12 shows a radiation pyrometer.

The radiation pyrometer "picks up" the radiant heat by means of a *lens* and focuses the heat waves onto a thermocouple mounted in a vacuum tube. The instrument used in recording the emf produced by the thermocouple is a potentiometer whose scale is calibrated in degrees. The thermocouple works in the same way as a thermocouple which makes direct contact with a hot substance as was shown in figure 2-1.

Since a thermocouple produces voltage which is proportional to the actual difference in its heated junction and its cold one, care must be taken in selecting the correct size of material and the type of protective tube. If the hot junctions have a significant mass, or if heat is transferred slowly because of some protective tube, the electrical response may lag far behind the environment in which the thermocouple assembly has been placed.

For this reason, the hot junction should be made as small as possible and the protective tube selected for minimum delay and attenuation.

Recently semiconductors have become popular for use as thermocouples. To produce electricity by using semiconductor devices, two semiconductor materials are used, one a P-type and one an N-type. Figure 2-13A shows how these materials are made.

The N-type semiconductor has a number of surplus electrons free to move around. The P-type semiconductor has such a lack of electrons that it is not able to supply enough electrons to fill its atomic structure. The lack of electrons then, in effect, creates holes or electron deficient spaces in the materials.

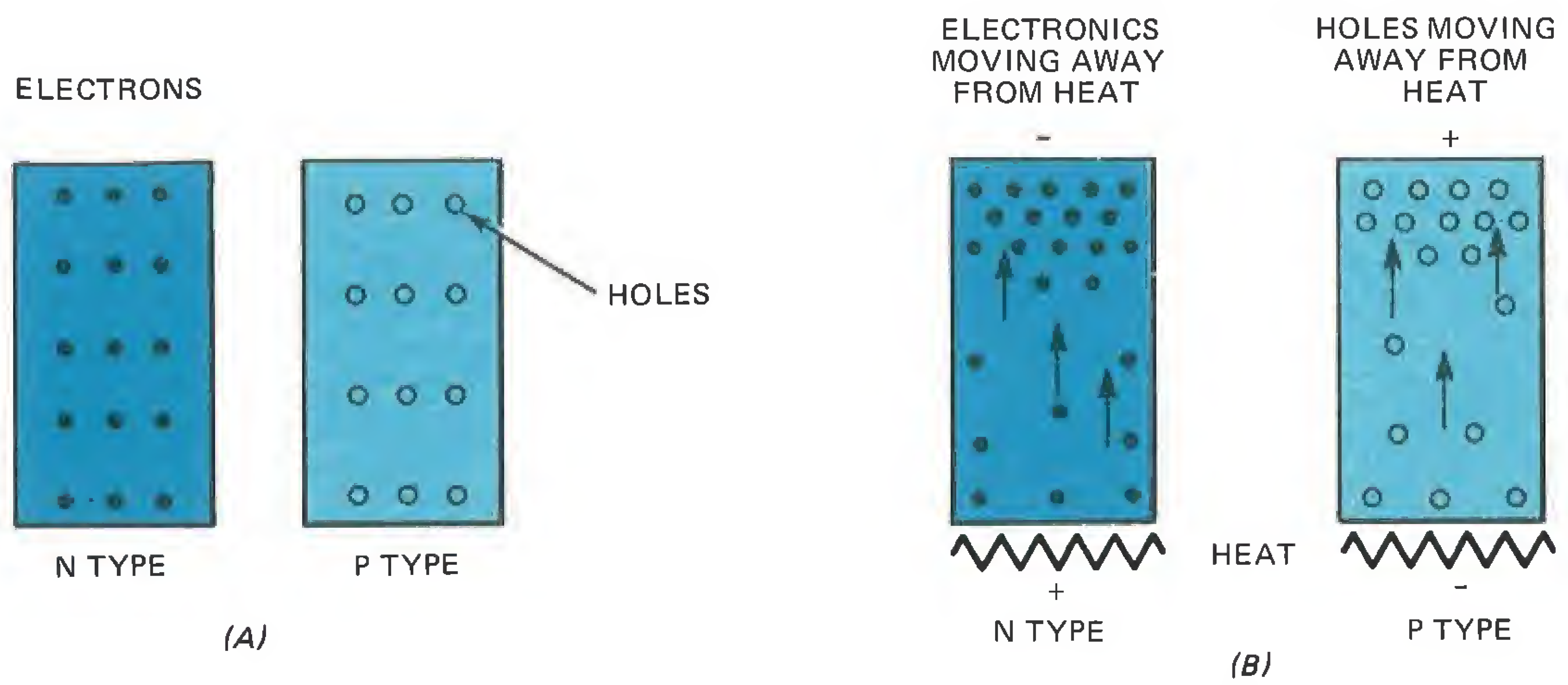


Fig. 2-13 (A) Even Distribution of Electrons and Holes
(B) Heat Moving Electrons in Two Materials

When a flame is placed under the N-type material, the electrons become agitated by the intense heat and accumulate near the top of the bar where it is cooler. The cool end becomes more populated with electrons than the hot end and thus becomes negatively charged with respect to the hot end. When the P-type material is heated, the majority carriers (holes) do as the electrons did in the N-type material, they migrate to the cool end. Since the holes represent missing electrons, the holes create a positive charge in the sense that there are fewer electrons in the cold end than are in the hot end of the material. Figure 2-13B shows how the N-type material becomes negatively charged at the cool end and positively charged at the hot end. It also shows how the P-type material becomes positively charged at the cool end and negatively charged at the hot end.

If the two materials are joined as shown in figure 2-14A there is a path for electron flow when heated as seen in figure 2-14B.

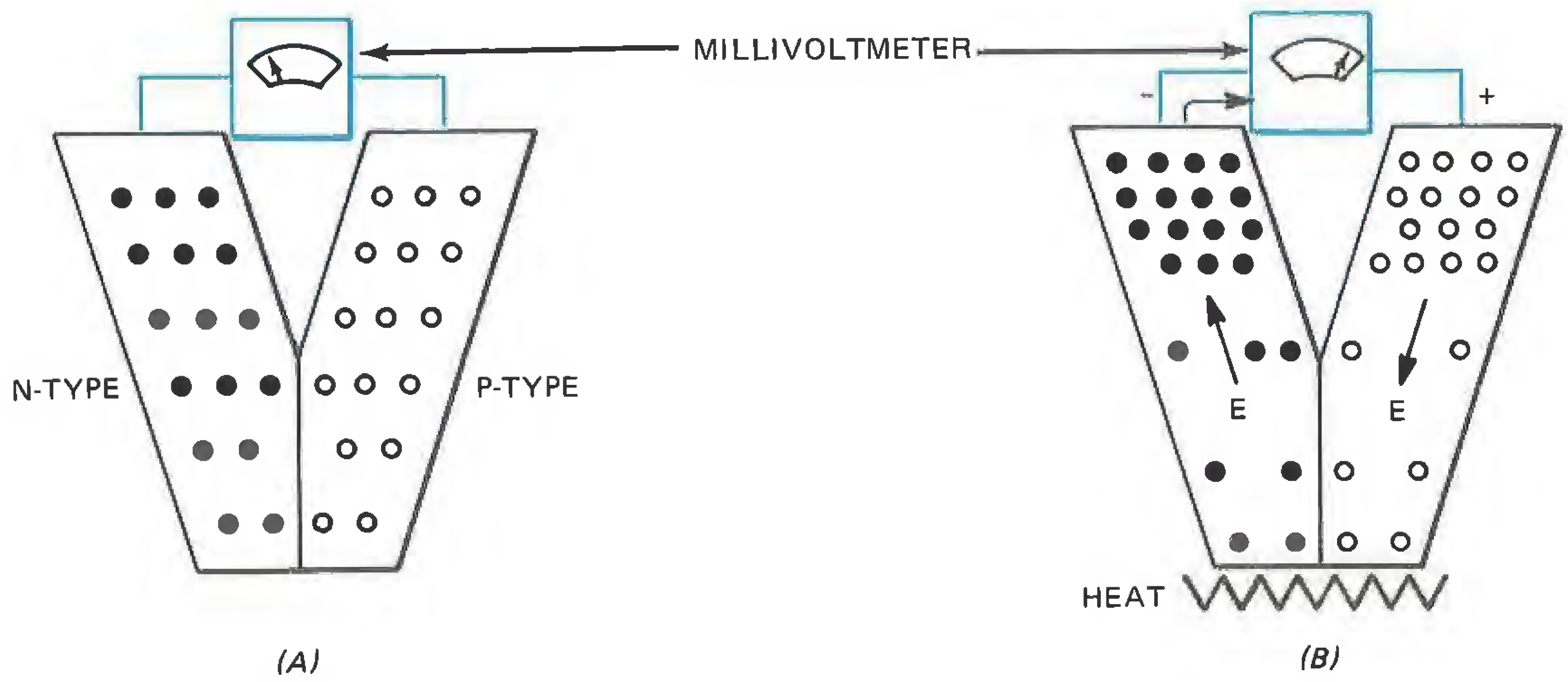


Fig. 2-14 (A) Materials Joined Before Heating
(B) Voltage Produced Because of Heating

Altenkirch showed in 1909 and 1911 that for both thermoelectric generators and refrigerators, materials with high thermoelectric coefficients, high electrical conductivities, and low thermal conductivities are needed to reduce heat transfer losses. With metallic thermocouples, these favorable properties are not available. It is only since semiconductor thermocouples have been introduced that reasonable efficient thermoelectric generators and refrigerators have become possible.

MATERIALS

- 1 Commercial thermocouple — copper constantan or equivalent
- 1 Pair thermocouple wire materials — chromel-alumel or equivalent
- 1 Millivoltmeter
- 1 Wrist watch (supplied by student)
- 1 Thermocouple tester
- 1 Bunsen burner

PROCEDURE

1. Connect the commercial thermocouple as shown in figure 2-15.

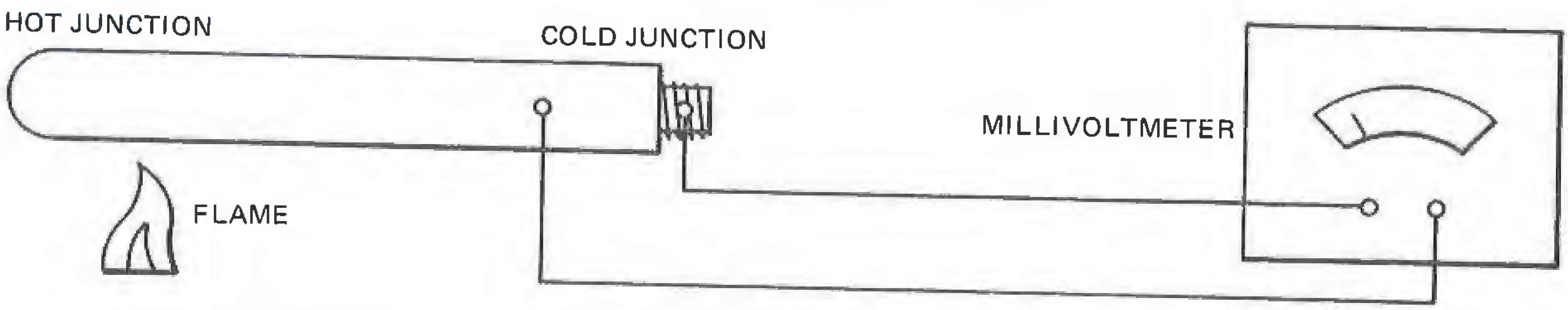


Fig. 2-15 Connection of the Commercial Thermocouple Circuit

2. Apply heat to the hot junction.
3. Record the voltage every 10 seconds in the data table, figure 2-17, until there is no increase in emf produced.
4. After a constant emf is reached, remove the heat and record the decrease in emf as the thermocouple cools.
5. Calculate the temperature for every change in voltage using the information in the discussion for the particular thermocouple material used.
6. Twist the bare ends of the laboratory thermocouple materials together.
7. Connect the laboratory thermocouple circuit as shown in figure 2-16.

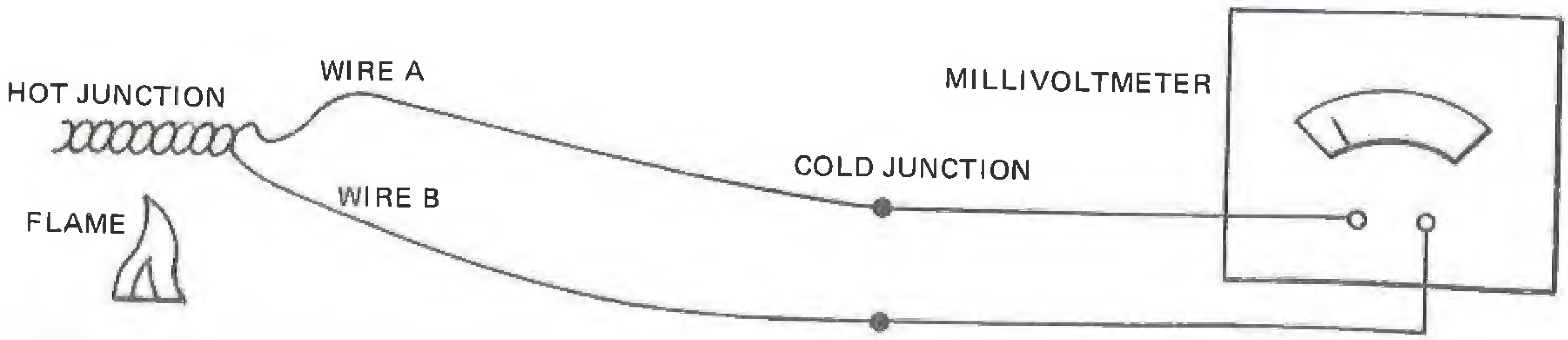


Fig. 2-16 Connection of the Laboratory-Constructed Thermocouple with the Millivoltmeter

Time in 10 Sec Periods	Millivolts	Temp. °F
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		
110		
120		
130		
140		
150		
160		
170		
180		
190		

Fig. 2-17 Millivolt-Temperature Table for a Commercial Thermocouple

HEAT APPLIED

HEAT REMOVED

Time in 10 Sec Periods	Millivolts	Temp. °F

Fig. 2-18 Millivolt-Temperature Table for Lab Constructed Thermocouple

8. Repeat steps 2 through 5 and record the results in the data table in figure 2-18. *Note: It must be remembered that emf is determined by temperature difference between hot and cold junctions; therefore, care must be taken in reading the meter and heating the hot junction for too long a period. This causes heat conduction and the cold junction temperature will increase.)*
9. Test the commercial thermocouple with the thermocouple tester and determine the approximate emf rating of the tester by observing the length of time it takes to energize the tester.

ANALYSIS GUIDE. Based on these experimental results explain how a thermocouple works. From the data obtained, draw graphs of the emf produced versus both time and temperature. Explain how the output changes with the temperature and how the output changes with heating time.

PROBLEMS

1. Explain how a thermocouple is used in a hot water control system.
2. Explain how a thermocouple might be used to control a mechanical clutch.

PRESSURE TRANSMITTERS

INTRODUCTION. It is often desirable to convert some measurement into a pneumatic signal which may be transmitted to a remote point for use there. In this experiment we will examine some of the principles of operation of a pressure transmitter.

DISCUSSION. One of the more common industrial measurements is that of *pressure.* Figure 3-1 illustrates an application in which a transducer is reacting to temperature and transmitting pressure energy to a mechanical valve.

Before getting into the operation of the pressure transmitter, a look at the basic characteristics of pressure is worthwhile. Many substances are found in the gaseous state with air being perhaps the most common. Air is a mixture of several gases in which oxygen and nitrogen predominate. The pressure normally measured is really an application of *Dalton's Law of partial pressures* which states that *the total pressure* P_T *is equal to the sum of the partial pressures,* P_a, P_b, *etc.* That is

$$\boxed{P_T = P_a + P_b + P_c + \ldots} \tag{3.1}$$

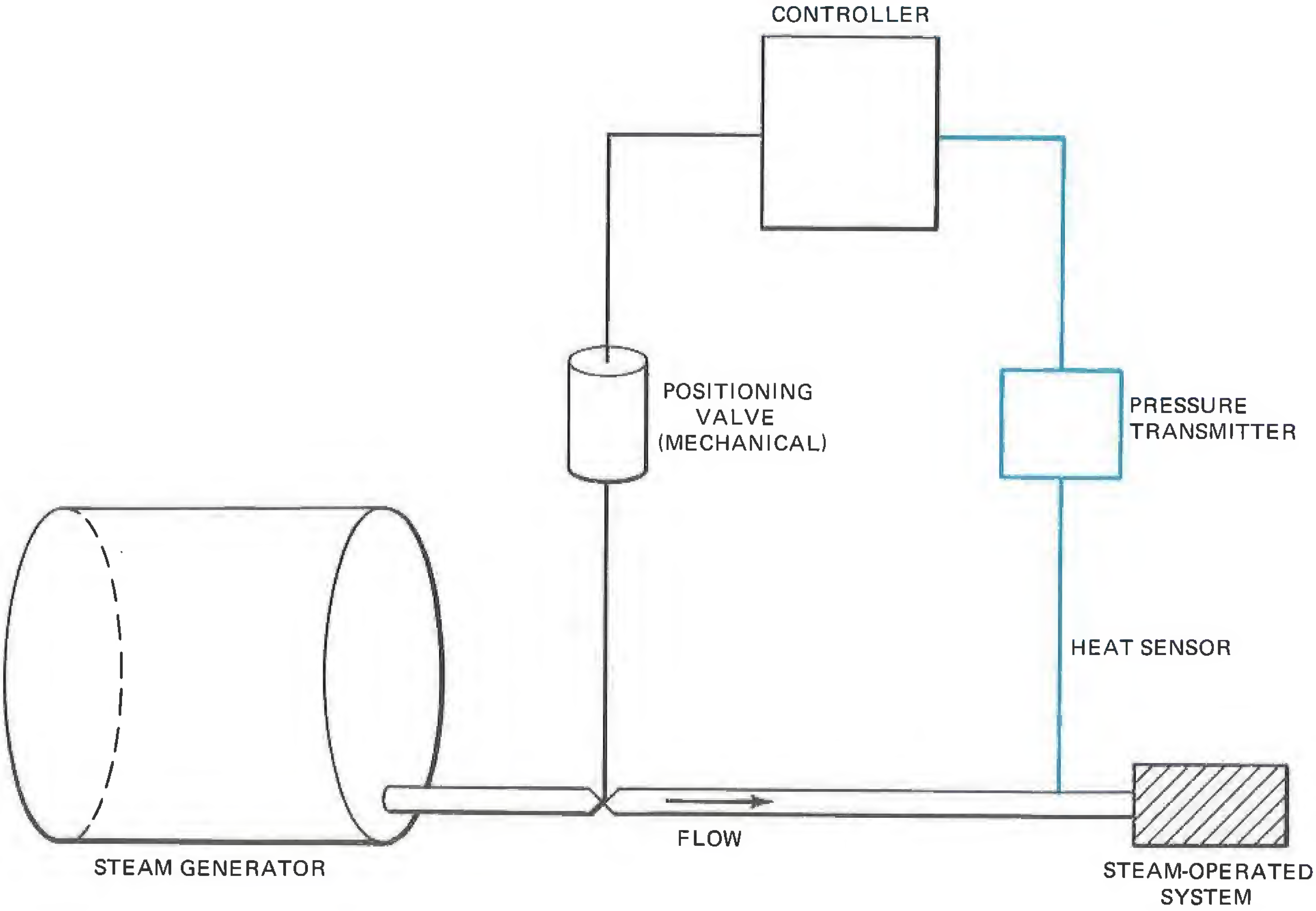


Fig. 3-1 A Pressure Transmitter System

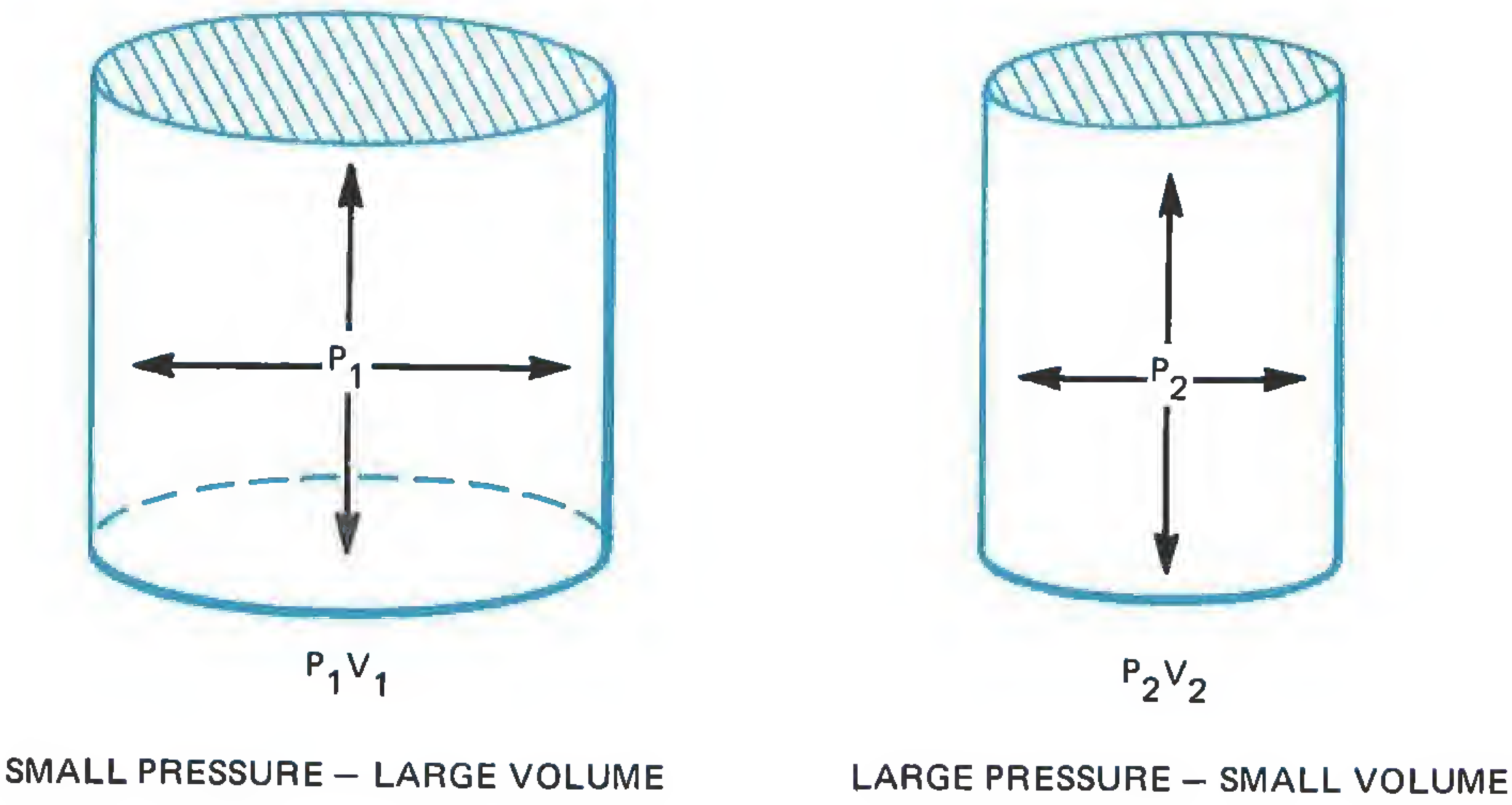


Fig. 3-2 Pressure Volume Relationships of a Fixed Amount of a Gas

Whenever a gas is put into a closed container, pressure is exerted in all directions. Suppose a gas at a certain pressure is put into a closed cylinder with a particular volume as shown in figure 3-2. Now suppose the volume is reduced by half. What will happen to the pressure? Because there is the same amount of gas in a smaller space, the pressure will increase. This relationship was first stated by Robert Boyle and is known today as *Boyle's Law.* The law states that, *if the temperature of a contained gas is not permitted to change, the product of the pressure and volume is constant.* Stated another way, the pressure is inversely proportional to the volume provided the temperature remains constant. Symbolically,

$$P_1V_1 = P_2V_2 \tag{3.2}$$

Since pressure, volume, and temperature are related, another law, *Charles's Law,* should be considered. The law simply states that *the volume of a given mass of an ideal gas kept at constant pressure expands by 1/273 of its volume at 0°C for each 1°C change in temperature.*

Symbolically, an equation may be written such that

$$V_t = V_o\left(1 \pm \frac{1}{273}\, t°C\right) \text{ at constant pressure}$$

or

$$V_t = \frac{V_o}{273}\,(273 \pm t°C) = KT \tag{3.3}$$

where

V_o = Volume at 0°C
V_t = Volume at t°C
$K = \frac{V_o}{273}$ a constant
T = Absolute temperature, degrees Kelvin
= 273 ± t°C

Both of these inter-relationships may be shown by the *general gas law* equation

$$\boxed{\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}} \tag{3.4}$$

Note that when the temperature of the gas is held constant so that $T_1 = T_2$, this law reduces to $P_1V_1 = P_2V_2$, which is Boyle's

Law. Also, when the pressure of the gas is kept constant so that $P_1 = P_2$, this law reduces to $V_1/T_1 = V_2/T_2$ which is Charles' Law.

The general gas law states that no matter what changes take place in a given mass of gas, the product of its pressure and volume divided by its Kelvin temperature remains constant.

Kelvin temperature is found by adding 273° to the Celsius degree reading such that

$$\boxed{K^\circ = C^\circ + 273^\circ} \qquad (3.5)$$

Fahrenheit temperature can be converted to Centigrade by the equation

$$\boxed{C^\circ = \frac{5}{9}(F^\circ - 32^\circ)} \qquad (3.6)$$

Pressure may be measured in a number of ways. Usually what is determined is the difference between the unknown pressure and atmospheric pressure. This difference is known as gage pressure and is read as psig. Experimental data has demonstrated that the molecular structure of the atmosphere exerts a pressure of about 14.7 psi at sea level which is equivalent to 76 cm of mercury. Suppose the pressure reading of a system is 10 atmospheres, the gage pressure would read 147 psi or 760 cm of mercury. If there were no atmospheric pressure, the absolute value of pressure at sea level would be zero since

$$\boxed{\text{Absolute pressure} = \begin{array}{c}\text{Gage pressure}\\ + \\ \text{Atmospheric pressure}\end{array}} \qquad (3.7)$$

It must be remembered that the pressure read from the pressure gage is not the absolute pressure. To the gage pressure reading, 14.7 psi must be added to have the absolute pressure.

Vacuum measurement is the measurement of pressure below atmospheric conditions. Pressures above atmospheric are normally read in psig or atmospheres. Pressure below atmospheric is usually read in inches of mercury; 29.92 inches of Hg is equivalent to 14.7 psi or approximately 2 in. of Hg for each pound of pressure. At this point let's pause and calculate the pressure reading below atmospheric that corresponds to 20 inches of Hg.

$$20 \text{ in. Hg} \times \frac{1 \text{ psi}}{2 \text{ in. Hg}} = 10 \text{ psi below atmosphere}$$

There are actually four ranges of vacuum

Medium, 1 in. Hg to about 29 in. Hg
Medium high, 1 to 10^{-3} torr (mm Hg)
High, 10^{-3} to 10^{-7} torr (mm Hg)
Ultrahigh, less than 10^{-7} torr (mm Hg)

Temperature measurements themselves are not normally transmitted over about 200 feet. However, a control center may be considerably farther than that. Therefore, in place of on-the-spot measurements, some suitable measurement transmission system is frequently used. Because pressure can be used to indicate temperature over a great distance, pressure transmitters can be used. They are economical, accurate, easy to install and come in several popular designs.

The most commonly used pressure transmitter is built with a baffle and nozzle to react as shown in figure 3-3. This mechanism

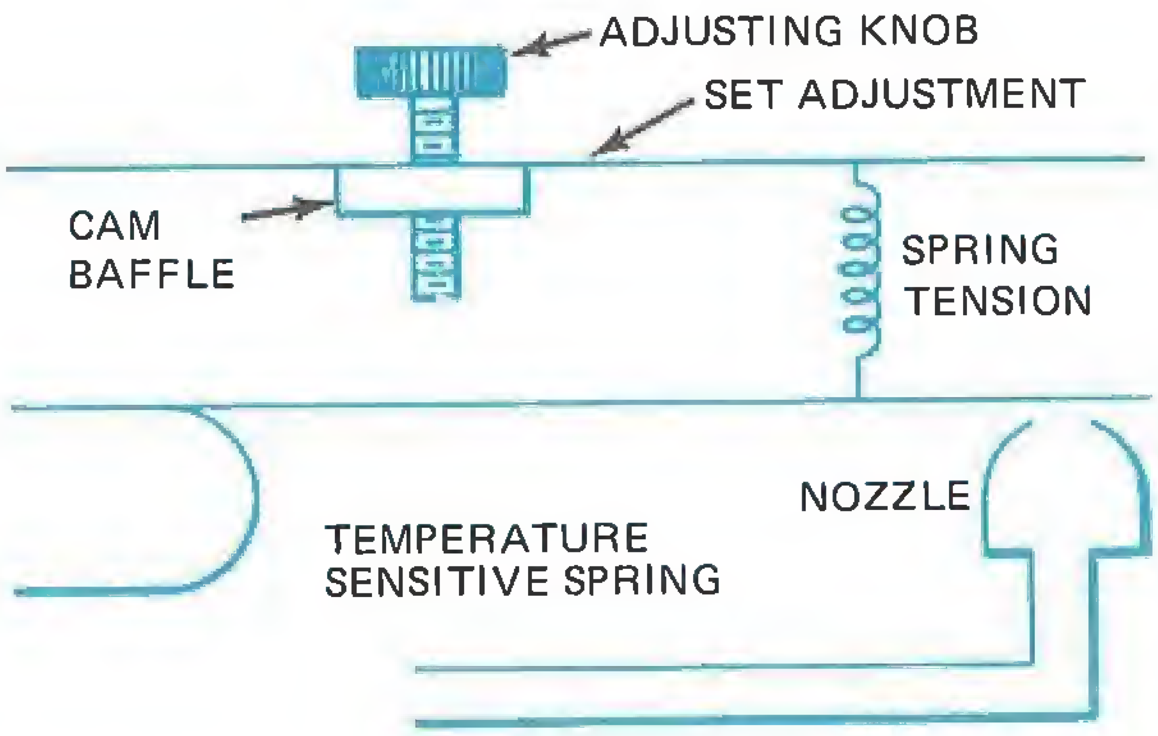


Fig. 3-3 Schematic of Pressure Transmitter

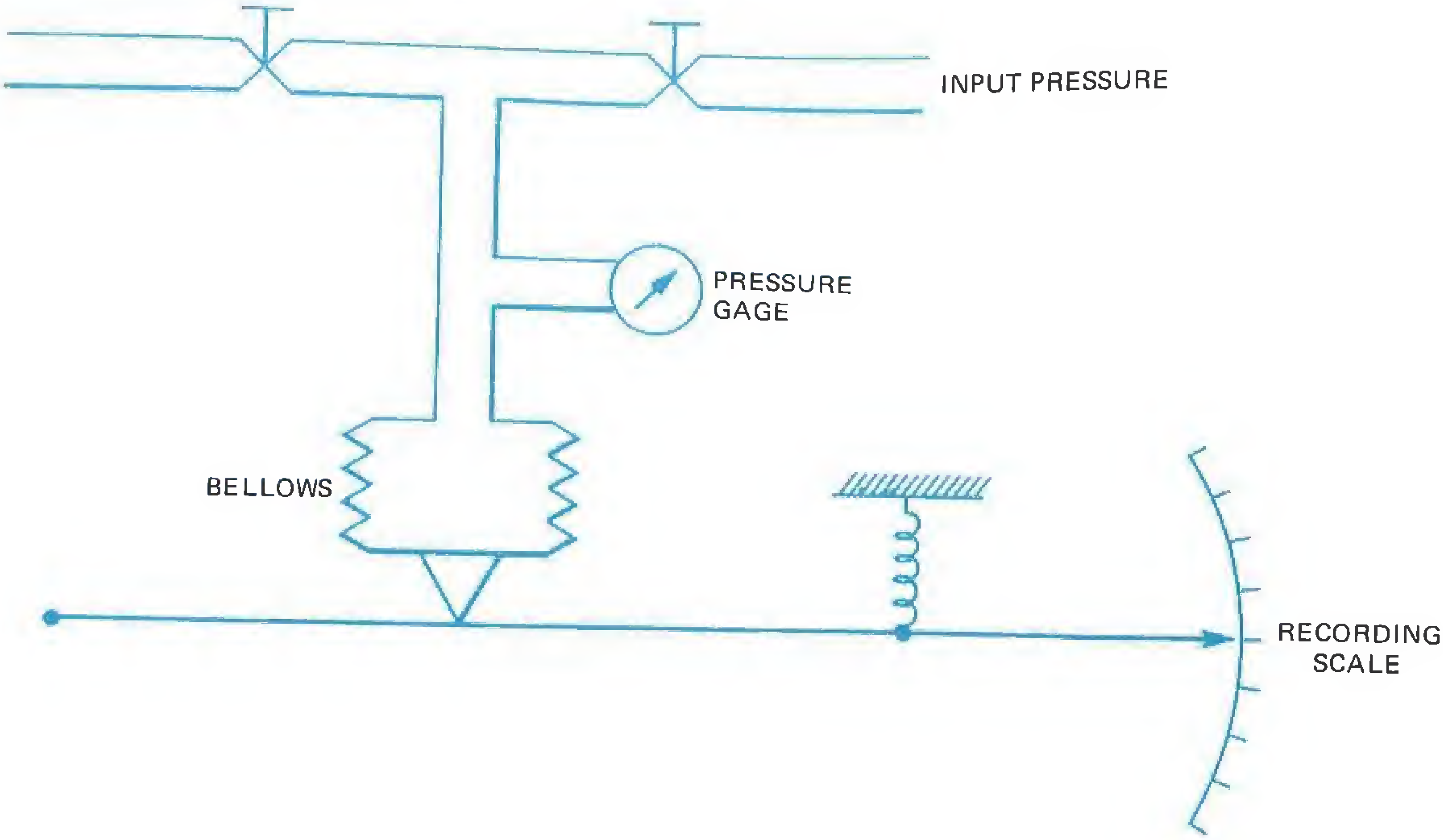


Fig. 3-4 A Schematic of a Recording Pressure Transmitter

may be, and often is, structurally more complex and may also serve as a recording as well as a transmitting element. Figure 3-4 shows one type of application.

A pressure transmitter is normally located in a position where it will sense pressure (Dalton's Law), volume (Boyle's Law), or temperature (Charles' Law). Any of these factors can cause a change which will be transferred by the pressure transmitter to some remote location. Perhaps the key principle of pressure transmission is based upon *Pascal's Law.* It says that *the pressure exerted on a confined fluid is transmitted undiminished in all directions and acts with equal force on equal areas and at right angles to them.* The diagram shown in figure 3-5 illustrates this principle.

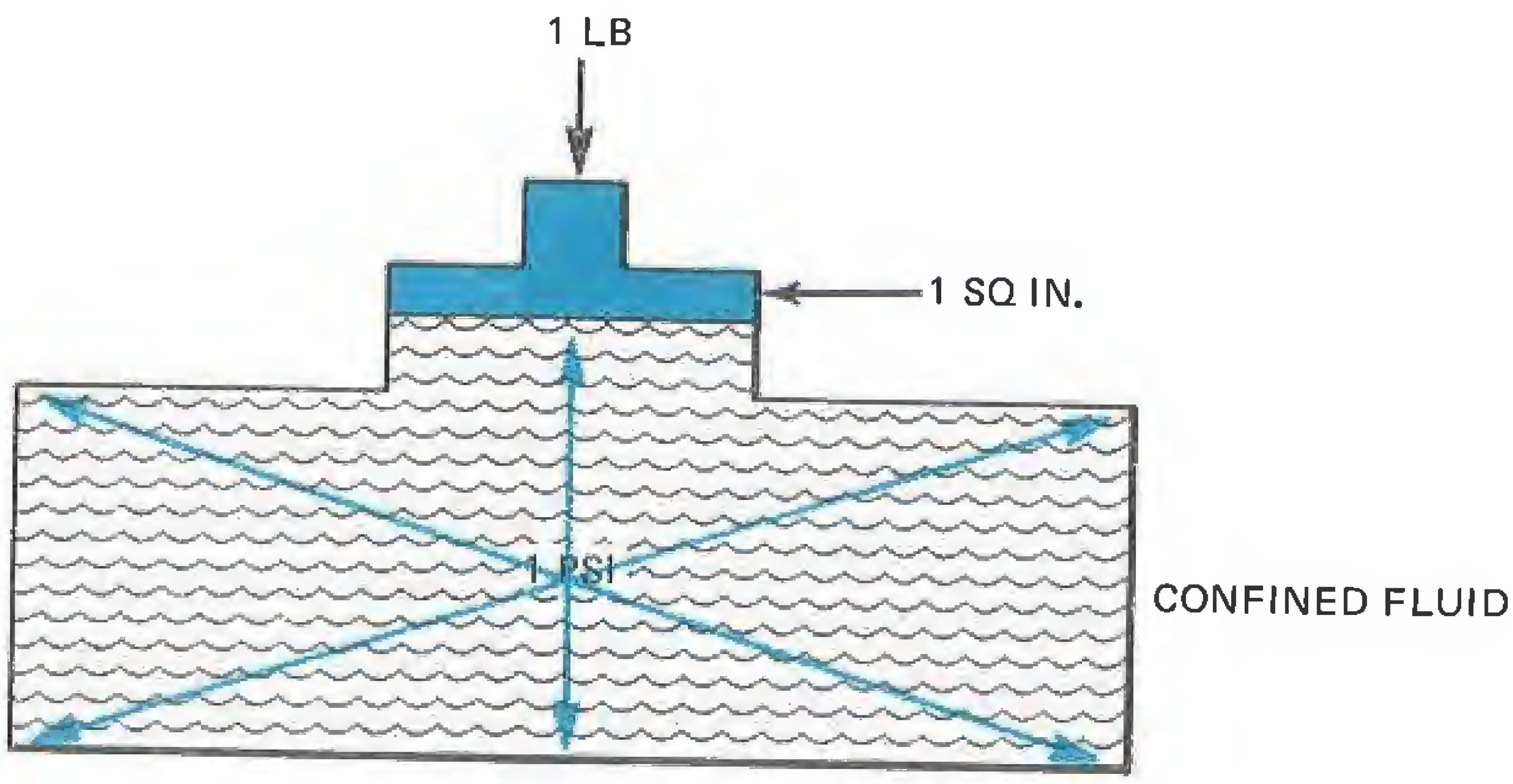


Fig. 3-5 Pascal's Law Illustrated

A symbolic representation of Pascal's law is given in the equation

$$\boxed{P = \frac{F}{A}} \qquad (3.8)$$

which states that the pressure is directly proportional to the force and inversely proportional to the area.

Suppose a pressure transmitter is actuating a valve whose diameter is four inches and requires 15 psig to operate. What is the force required to close the valve?

$$F = PA = 15\ \text{lb/in.}^2 \times 2\pi r^2\ \text{in.}^2$$

$$F = 376.80\ \text{lbs}$$

Another point that must be considered in the operation of the pressure transmitter is the nozzle clearance. If the baffle is brought close to the nozzle, there begins to be a restriction of the air flow. When the baffle is brought still closer to the nozzle, the flow is almost totally cut off. The maximum pressure change occurs for a baffle movement of 0.006 inches. But we usually are not looking for maximum pressure changes because the amount of pressure, temperature, or the mechanics necessary to accommodate maximum changes is quite demanding. The plot in figure 3-6 shows the relationship of pressure to nozzle clearance. Experience and design have also shown that for every *0.001 inch change in clearance a pressure change of 2 psi occurs.*

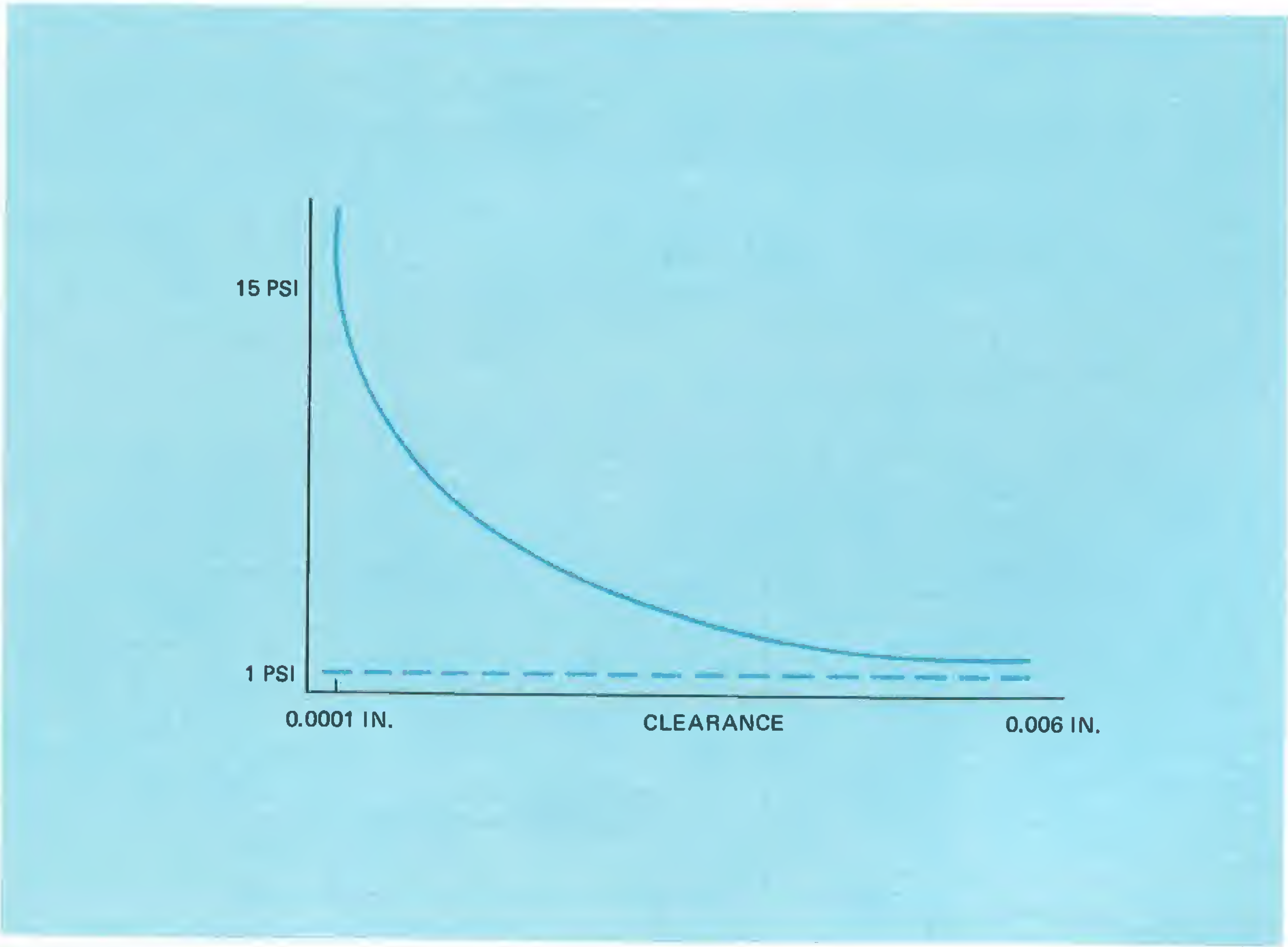


Fig. 3-6 Nozzle Clearance vs Pressure

In this experiment we will use a pressure transmitter system with the pressure relay as shown in figure 3-7. An air supply with component parts will be interconnected and the by-pass pressure which operates the mechanism will be determined for different input pressures. Normally the system would have a valve, as shown in figure 3-8, but in our experiment the valve will be replaced by a pressure gage to indicate how the pressure is dependent on the nozzle opening.

The transmitter will react to pressure or temperature. When the air supply is turned

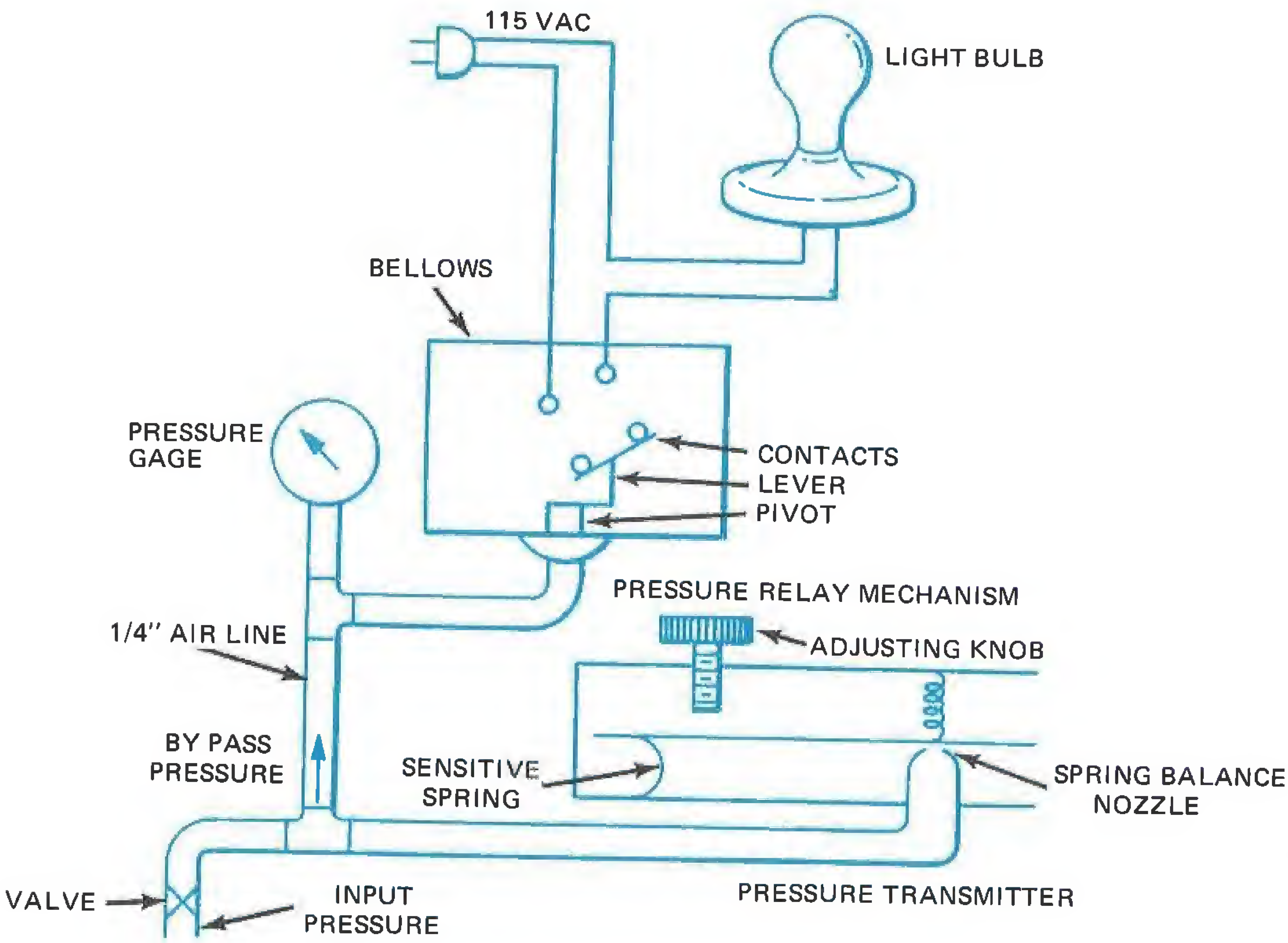


Fig. 3-7 A Schematic of a Pressure Transmitter System with Components

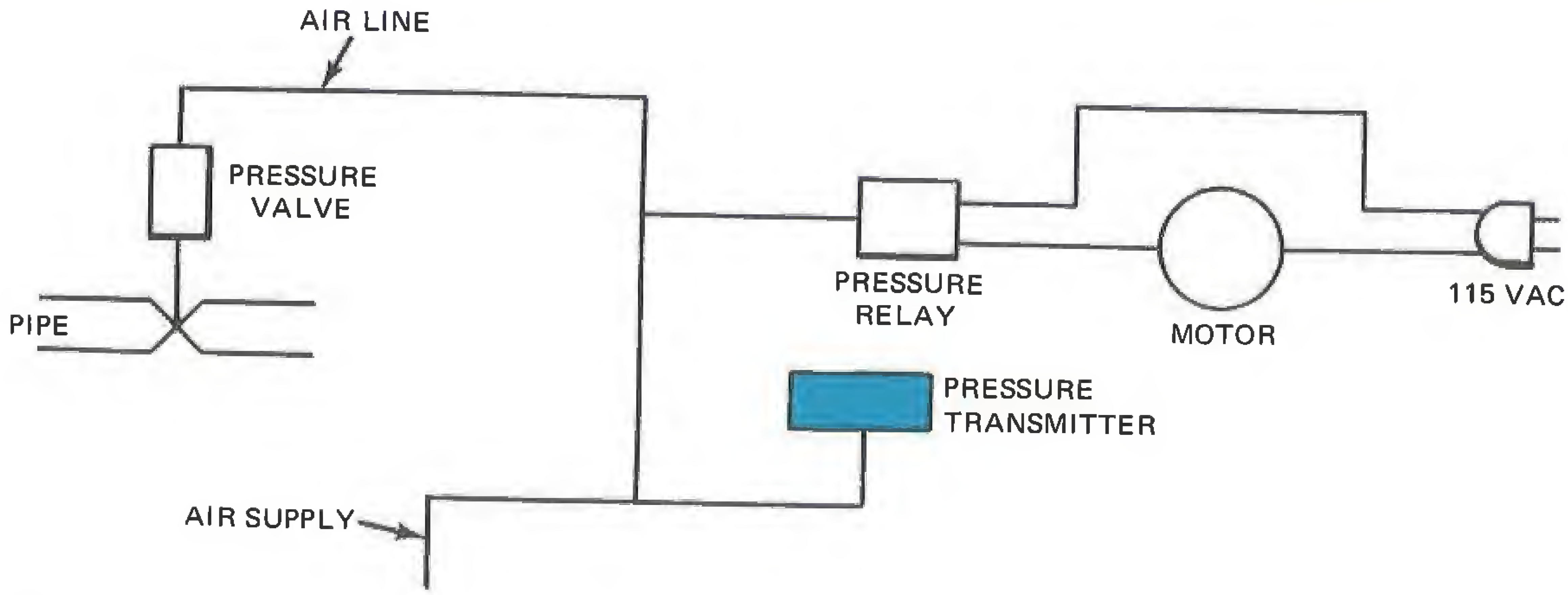


Fig. 3-8 Schematic Showing a Pressure (Pneumatic) Valve Actuated by a Pressure Transmitter

on, air is distributed through the system. As the reaction occurs the nozzle partially opens and the pressure is reduced. As the temperature is reduced, the nozzle opens further and the pressure reduces to a point where the pressure relay will open, disconnecting the electrical energy from the motor. As the pressure reduces, the pressure valve opens.

This type control is common in heating systems using hot water or steam in the heating coils. The system is made up of a heating coil similar to the one found in a car. A fan blows air through the coil into the room. When the room gets cold, the nozzle opens to a point that causes the valve pressure to drop. When the pressure reaches a set point, the pressure relay opens, shutting off the fan, and after still more reduction the valve opens, allowing hot water into the coil. Due to air convection over the hot coils, the room temperature starts getting warmer. As the room gets warmer, the nozzle clearance on the transmitter gets smaller; causing more pressure on the pressure relay and the pressure valve. At a set pressure, the pressure relay will close, turning on the fan, and with additional reduction in nozzle clearance, the pressure to the valve will close off the hot water to the coils. This cycle goes on continuously to heat the room.

MATERIALS

1 Pressure relay
1 Pressure transmitter
1 Light bulb and socket
1 Pressure gage 0-30 psi
1 1/4 in. plastic tubing with suitable connections
2 1/4 in. plastic tubing Tee connectors
1 Remote bulb thermometer

PROCEDURE

1. Set up the apparatus as shown in figure 3-9.

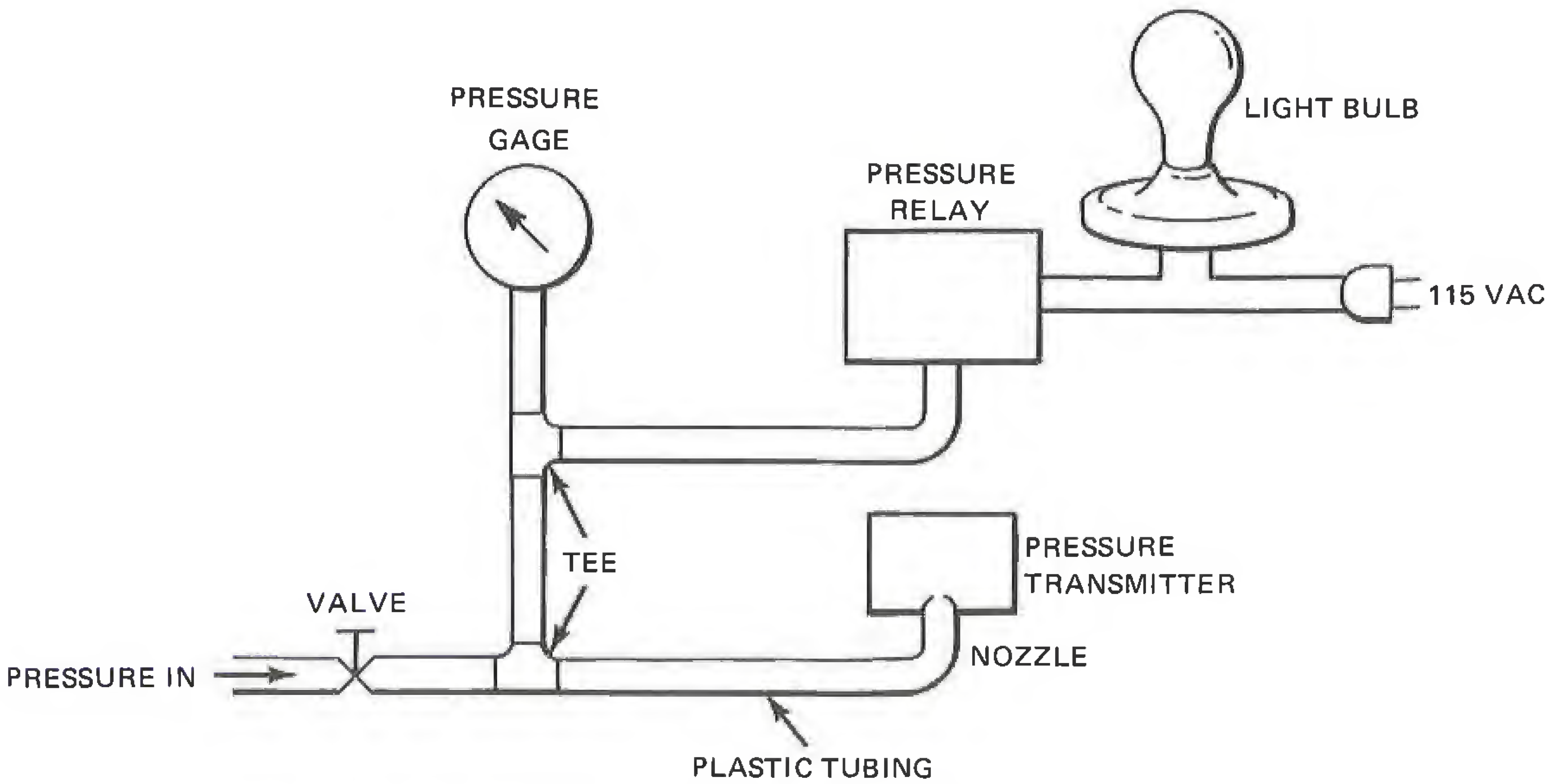


Fig. 3-9 Experimental Setup I

2. Set the pressure relay to close at 15 psi and to open at an eight or nine psi difference.
3. Increase the input pressure until the gage reads 15 psi with the pressure transmitter indicator at 60° or at a value that closes the nozzle clearance completely.
4. Record the pressure at which the light bulb comes on.
5. Increase the temperature indicator in 2°F increments and record the corresponding pressure in data table, figure 3-11.
6. Record the pressure at which the light bulb goes off.
7. Set the indicator back to 60°. Change the relay to close at 20 psi. Increase the input pressure to 20 psi.
8. Repeat steps 4 through 6.
9. Change the relay to close at 25 psi.
10. Repeat the experiment for 25 psi input pressure.
11. Rearrange the apparatus as shown in figure 3-10.

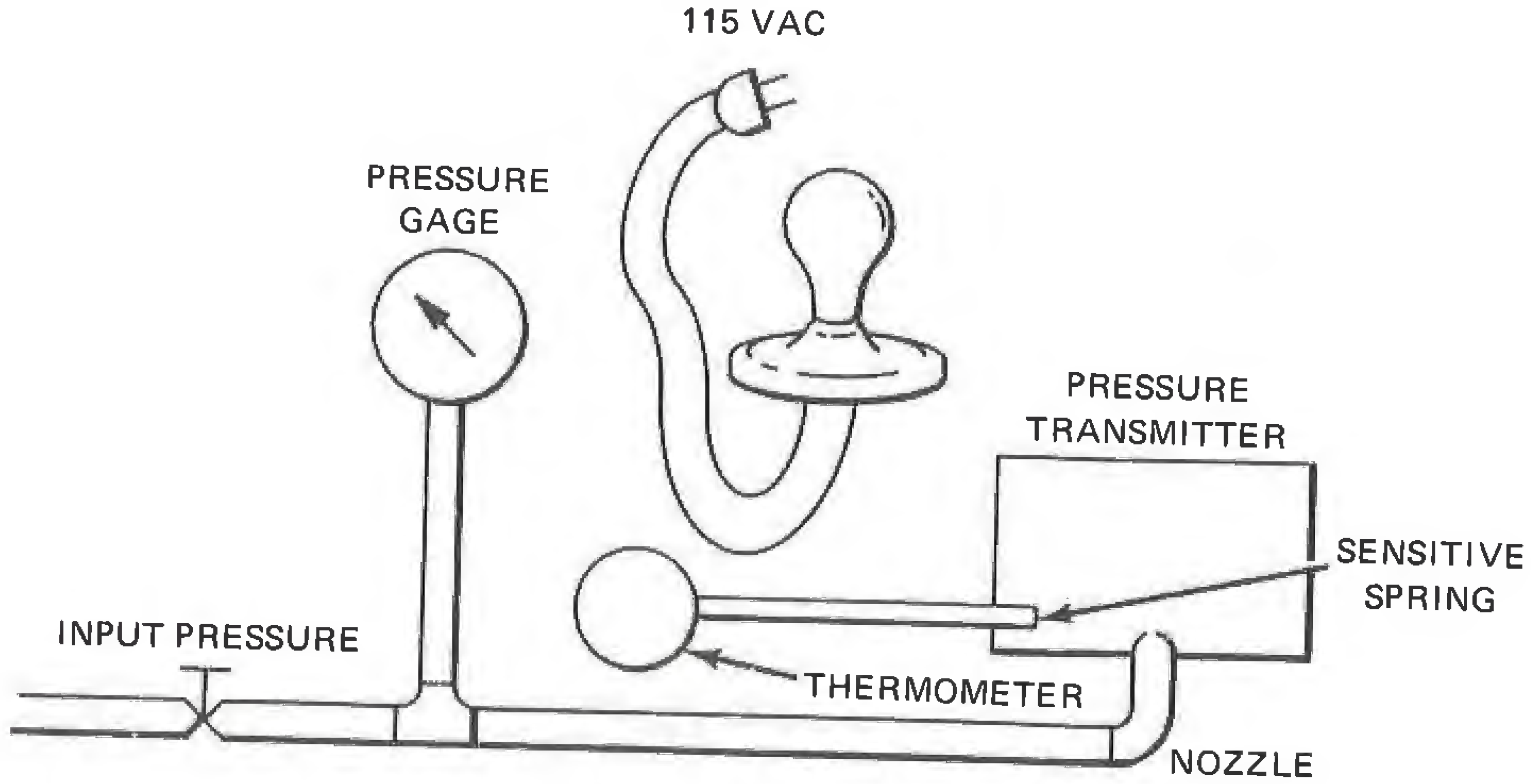


Fig. 3-10 Experimental Setup II

12. Place the remote bulb thermometer next to the sensitive spring.
13. Place the light bulb at a position where it can be used as a source of heat to warm the sensitive spring.
14. Increase the input pressure to 15 psi with the nozzle clearance shut off.
15. Place the heat indicator at its highest temperature. The pressure should be zero on the gage.
16. Turn on the light bulb and record the pressure for every 5°F change in temperature. Record the values in the data table.

15 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

20 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

25 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

Pressure Versus Temperature Indicator

Pressure	Relay On	Relay Off	Δ Pressure
15			
20			
25			

Relay Response

Temp	Pressure
75	
80	
85	
90	
95	

Pressure Versus Actual Temperature

Fig. 3-11 The Data Tables

ANALYSIS GUIDE. Plot a graph of pressure versus the temperature indicator values for all three input pressures. Also plot a graph of actual temperature versus pressure. It should be apparent from the first set of graphs how the pressure is dependent on the temperature setting. From the second graph it should be apparent how the actual temperature affects the movement of the sensitive spring.

PROBLEMS

1. At 15 psi a 15-cu. in. volume is at a temperature of 75° F. What is the new volume if the temperature is reduced to 70° F and the pressure is reduced to 0 psi?

2. Assuming a constant volume, with initial conditions of 15 psi and 80° F and the final pressure at 1 psi, determine the final temperature.

3. Suppose a pressure transmitter is operating at a pressure of 10 in. Hg and 70° F. If the final pressure is 5 psi, what is the final temperature?

4. Explain how the temperature setting affects the pressure transmitted by the pressure transmitter.

experiment 4 PIEZOELECTRIC EFFECT

INTRODUCTION. Piezoelectricity is one of the phenomena of nature that makes possible the changing of one form of energy to another. In this particular case mechanical motion is converted into electrical potential. In this experiment we will examine the characteristics of piezoelectric materials.

DISCUSSION. When a mechanical pressure is applied to a crystal of the Rochelle salt and Tourmaline type, a displacement of the crystals causes a potential difference to occur. When a voltage is applied across the crystal, a deformation of the crystals results. These characteristics are known as the piezoelectric effect.

This phenomenon was discovered by the Curie brothers in 1880. The word "piezo" is from the Greek, meaning *to press*. The effect is only temporary. As long as the pressure changes, the potential difference exists. The recovery time for the crystals to resume their original shape is practically instantaneous. For this reason piezo crystals are used to measure pressure, stress, or acceleration.

In 1916 a Frenchman by the name of Paul Langevin devised the first major application of the piezoelectric effect. He used it in developing an ultrasonic submarine detector. The device was made of a quartz element placed between two metal electrodes. When an electric signal was applied to the quartz, high frequency mechanical vibrations were transmitted through the water. These vibrations were reflected back to a second quartz crystal after hitting an object in the water such as a submarine. By knowing the speed the wave travelled in the water, he could determine the distance the submarine was away from him. This device led the way to modern-day sonar.

As time went on more information was learned about the quartz crystal. During World War II, the United States used over 50,000,000 quartz crystal elements. Bell Telephone Laboratories developed quartz crystals as wave filters in multichannel telephony work.

In the 1930s the "crystal" phonograph pickup and microphone were discovered. These devices used Rochelle salts as the piezoelectric element.

In 1958 synthetic quartz crystals became available alleviating the necessity of using only natural crystals.

As mentioned earlier, piezoelectric materials can generate an electric potential under pressure; conversely, they can change their physical dimensions when subjected to an electrical charge. Figure 4-1 shows this pictorially.

Figure 4-1(A) represents the motor mode of operation, while figure 4-1(B) represents the generation mode. The ability of the material to convert mechanical energy into electrical, or vice versa, is determined by its electro-mechanical coupling coefficient, denoted by a small k.

For a piezoelectric element under pressure, part of the energy will be converted to an electric potential which will appear on op-

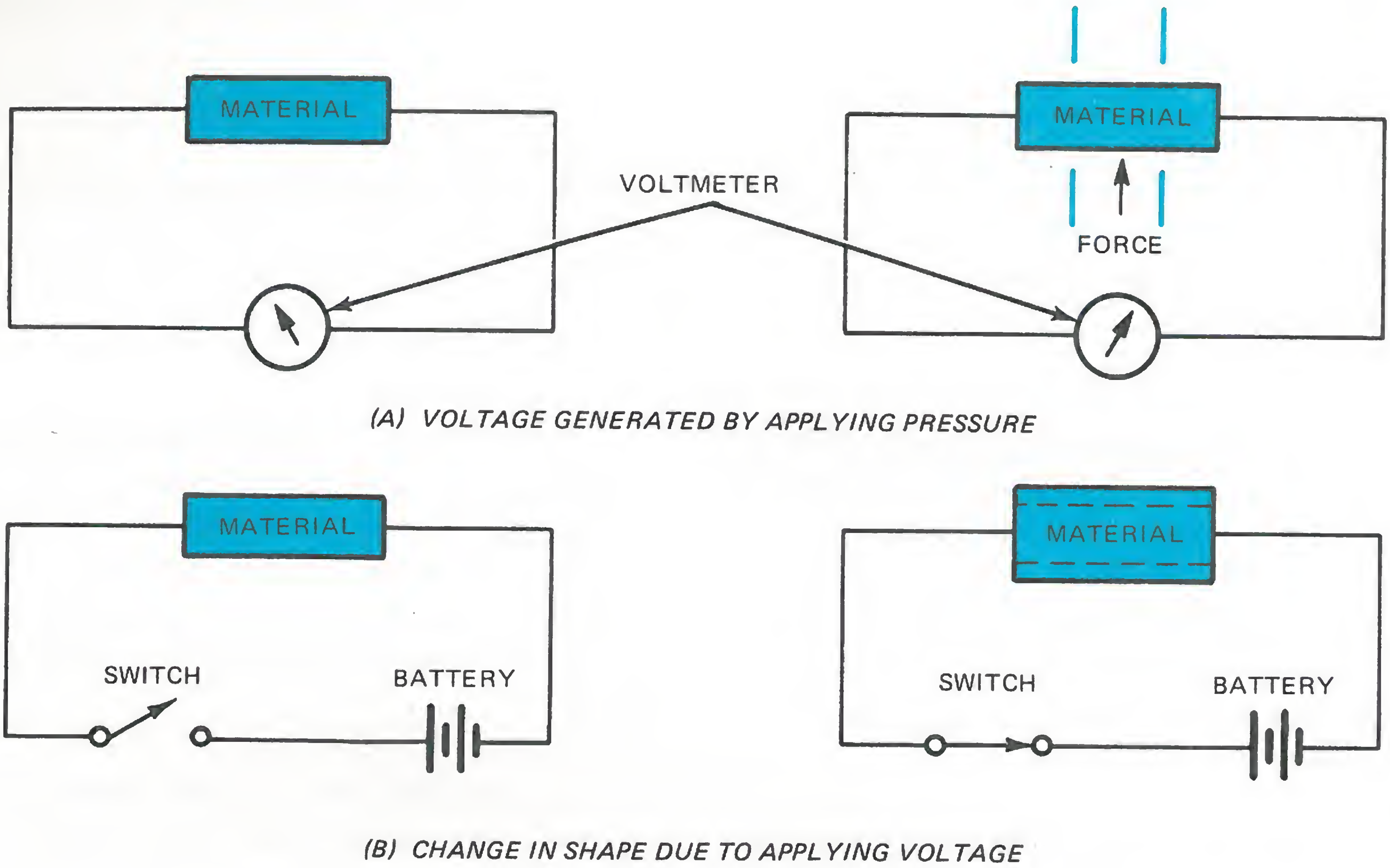


Fig. 4-1 Effects of Pressure and Voltage on Piezoelectric Material

posite faces of the element, analogous to the charge on the plates of a capacitor. The rest of the applied energy is converted into mechanical energy, analogous to a compressed spring. When the pressure is removed, it will return to its original shape and also lose its electric charge. From these relationships the following formulas have been derived for k.

$$k^2 = \frac{\text{mechanical energy converted to electrical energy}}{\text{applied mechanical energy}}$$

$$k^2 = \frac{\text{electrical energy converted to mechanical energy}}{\text{input electrical energy}}$$

There are other properties of piezoelectric materials. Some of these properties for some materials are given in the table in figure 4-2.

For a given force (Newtons) exerted on a mass of piezoelectric materials, there will be a given number of electrons given off (Coulombs). Rochelle salts at room temperature give off the greatest number of electrons per unit of force of the materials listed in figure 4-2. In 1940 Barium Titanate was developed by synthetic means. It resembles Rochelle salt in that its voltage produced for a certain pressure is approximately the same, but it offers the advantage of not being water soluble and it will operate at higher temperatures. Figure 4-3 lists the upper temperature limit for some of the piezoelectric materials.

Type	Coulomb/Newton	Volume (Ohm/m) Resistivity	Coupling Coefficient
Quartz	2.3×10^{-12}	1×10^{12}	10.5%
Tourmaline	1.9×10^{-2}	0.1×10^{12}	10%
Rochelle Salts @30°C	550×10^{-12}	10×10^{9}	76%
Ammonium Dihydrogen Phosphate	48×10^{-12}	0.1×10^{9}	32%
Lithium Sulphate	16×10^{-12}	10×10^{9}	38%

Fig. 4-2 Piezoelectric Materials

Material	Temperature Limit
Natural	
Quartz	550
Ammonium Dihydrogen Phosphate	120
Rochelle Salts	45
Synthetic	
Barium Titanate Ceramic	100
Lead Titanate Zirconate (45/55)	300
Lead Metaniobate	500

Fig. 4-3 Temperature Ranges of Piezoelectric Materials

The volume resistance listed in figure 4-2 is a measure of the resistance of the material for a certain volume of material. The volume resistance for quartz is 10 times greater than that for Rochelle Salts.

The coupling coefficient listed represents the efficiency of the crystal as an energy converter; that is, mechanical to electrical or vice versa.

The main applications of quartz are in transducers for the measurement of high level, high frequency transient pressures (engine indicators or blast-pressure gages). Artificial quartz is normally preferred because it is more pure.

Tourmaline has low sensitivity and is a semi-precious stone which makes it costly. Therefore, it is not normally used in transducers.

Rochelle salts plays a leading role in phonograph pick-ups and microphones. From the table in figure 4-2 it can be seen that it

has a high sensitivity. High sensitivity and high permittivity are of great importance in these applications.

Ammonium dihydrogen phosphate is similar to Rochelle salt except that it has lower sensitivity and permittivity.

Lithium sulphate has high sensitivity to hydrostatic pressure, but has very low permittivity.

Piezoelectric transducers can be divided into two kinds: motor-action transducers and generator-action transducers. In the motor-action mode, the deformation of the material is determined by the amplitude and the frequency of the voltage applied. In the generator-action mode, the voltage produced is determined by the pressure and the frequency of the applied pressure. Of course, one must consider that the amount of voltage generated or pressure produced is dependent on the physical size of the element.

Piezoelectric transducers are widely used in the military and industry. One type transducer is the piezoelectric shear accelerometer which accurately measures the vibrations of various mechanical objects on which it is mounted. Vibrations picked up at the base of the accelerometer produce corresponding shear stresses in the walls of the piezoelectric elements. The stresses produce proportional voltage output variations which are amplified and fed to an oscilloscope or chart recorder.

Another piezoelectric transducer is the compression accelerometer. Vibrations applied to the base produce pressure vibrations which produce voltage variations that are amplified and fed to an indicating device.

Another transducer is an underwater sound transducer. It is used to detect and analyze underwater pressures and sound waves. The unit is made with a stack of ammonium dihydrogen phosphate plates coupled to the water through a rubber housing with oil surrounding the plates.

One type of ultrasonic transducer is used in cleaning applications. The transducer creates a large amount of energy and is coupled to a tank of cleaning liquid. The energy causes cavitation in the liquid and when used with a proper cleaning agent it produces rapid cleaning. The piezoelectric material is mounted on the bottom of the tank with an applied AC signal of a high frequency corresponding to the resonant frequency of the material. The transducer vibrates at its resonant frequency, generating vibrations of high amplitude in the liquid within the tank.

An interesting transducer used to create high voltages is the piezoelectric spark pump. It consists of two piezoelectric materials mounted end to end. When pressure is applied to the ends, a voltage, sometimes as high as 20,000 volts, is produced. This generator is sometimes used for internal-combustion engine ignition systems, or whenever a pressure-produced source of very high voltage is practical. Figure 4-4 illustrates this application.

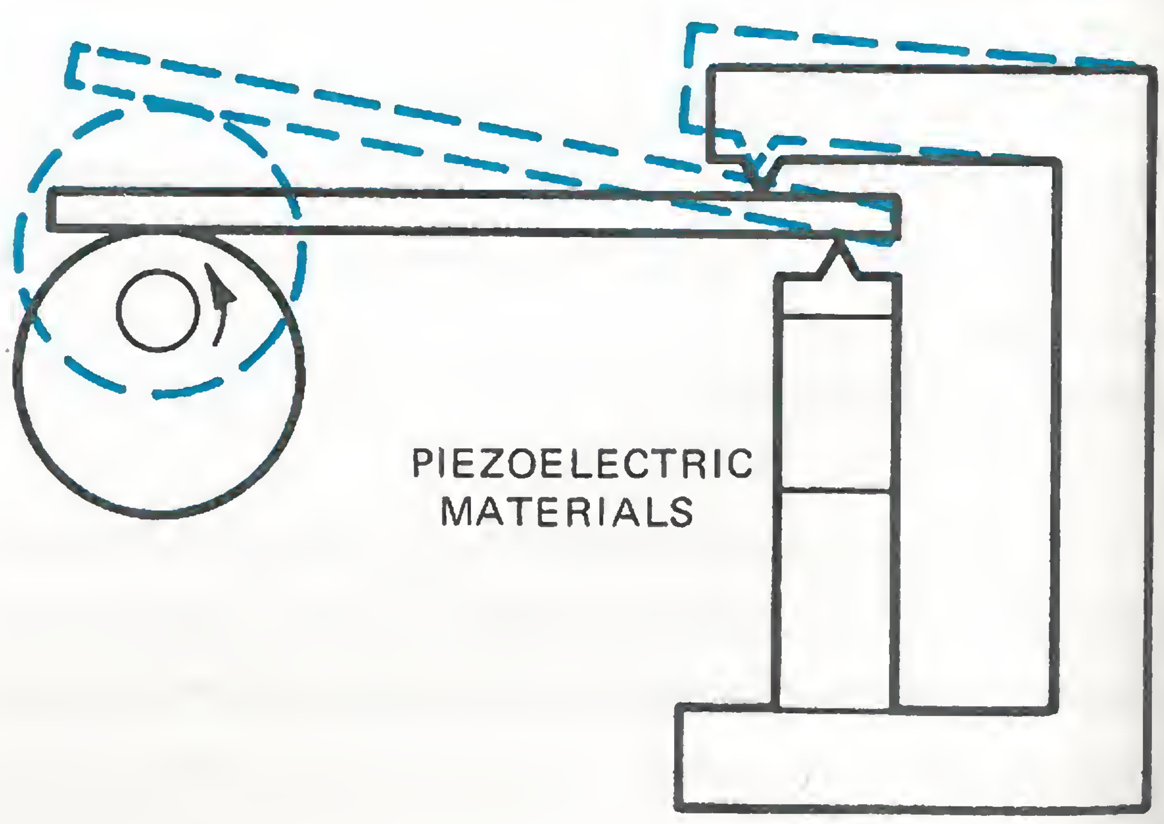


Fig. 4-4 Piezoelectric Transducer - Spark Pump

When generating a voltage by use of a piezoelectric material, the needle of a detecting meter will move one way for a pressure applied in one direction, and it will move the other way for a pressure applied in the other direction. The voltage will only be generated as long as the pressure applied to the piezoelectric element is changing. There is no output after the pressure becomes constant. The amount of voltage produced is a function of how rapidly pressure is applied to the material.

MATERIALS

- 1 Shaft hanger
- 1 Piezoelectric cell
- 1 Breadboard
- 1 Springbalance post with clamps
- 1 Springbalance
- 1 Steel ball pendulum (1 in. dia.)
- 1 Oscilloscope
- 1 Steel rule 6 in. long
- 1 Sheet of linear graph paper
- Misc. hardware as needed

PROCEDURE

1. Measure and record the weight of the steel pendulum ball (w).
2. Assemble the experimental setup shown in figure 4-5.

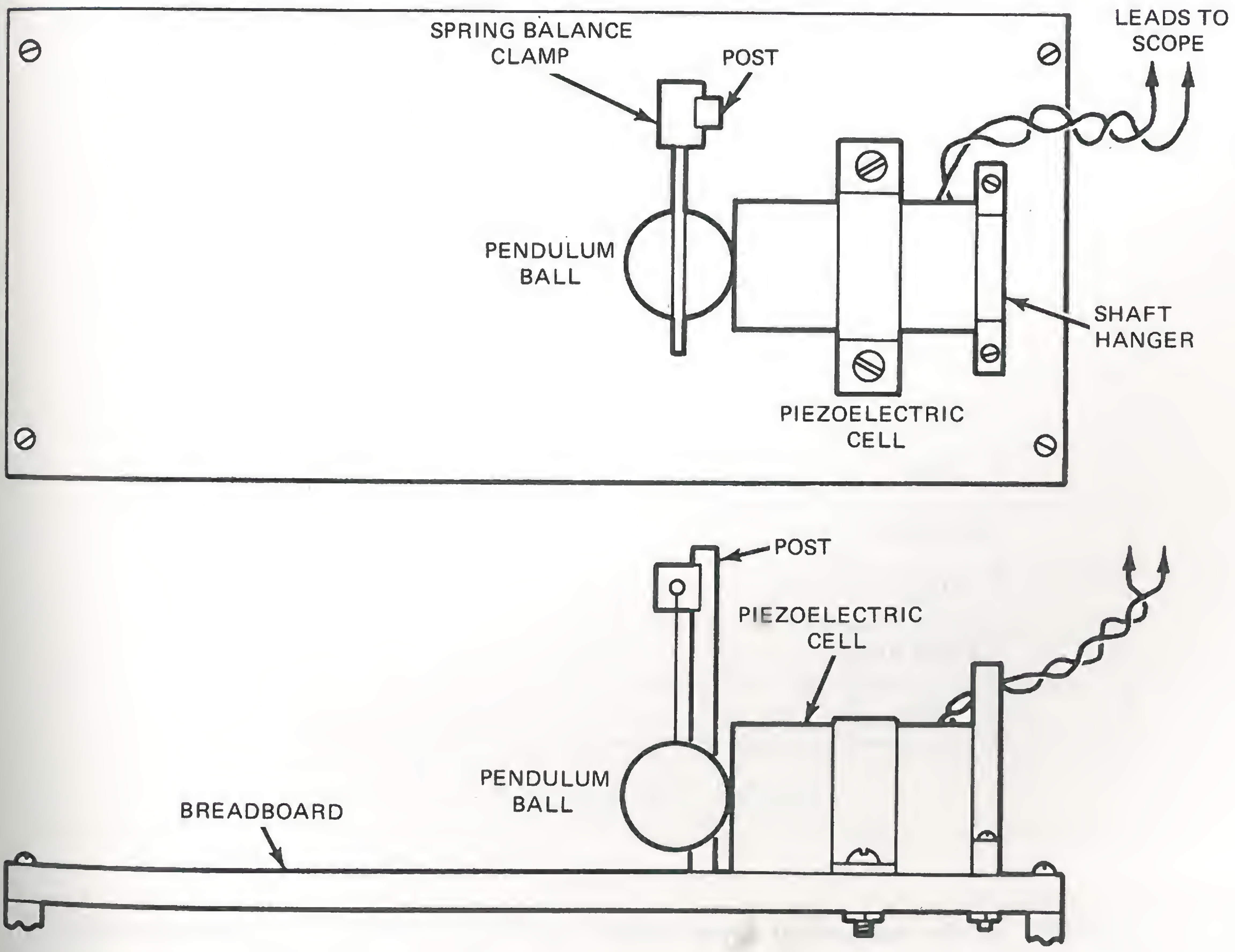


Fig. 4-5 The Experimental Setup

3. Connect the piezoelectric cell to the vertical input of the oscilloscope.

4. Adjust the pendulum length so that the center of the ball is lined up with the center of the piezoelectric cell.

5. Carefully pull the pendulum ball to the left until its center is one inch above the center line of the piezoelectric cell.

6. Release the ball and observe the oscilloscope trace. Repeat this process several times while adjusting the oscilloscope sweep and sensitivity. The scope is properly adjusted when you can measure the piezoelectric cell output pulse accurately.

7. Compute and record the potential energy of the pendulum ball (PE = wh) for vertical displacements of 1, 1-1/2, 2, 2-1/2, 3, 3-1/2, 4 inches, respectively

8. Pull the pendulum ball to the left until its center is one inch above the center line of the piezoelectric cell.

9. Release the ball and measure the piezoelectric output pulse height when the ball strikes the cell. Record this value as E in the data table.

10. Repeat steps 8 and 9 three times, then compute the average output pulse height. Record all of the values.

11. Repeat steps 8, 9, and 10 for all of the vertical displacements given in step 7.

12. Plot a curve of the potential energy of the ball versus the average pulse height.

w	h	PE	E_1	E_2	E_3	E_{ave}
	1 in.					
	1-1/2 in.					
	2 in.					
	2-1/2 in.					
	3 in.					
	3-1/2 in.					
	4 in.					

Fig. 4-6 The Data Table

ANALYSIS GUIDE. In the analysis of these results you should consider the extent to which the piezoelectric cell responded to the impact of the ball. Was the plotted relationship a linear one? Was *all* of the ball's energy expended on impact? How do you know?

PROBLEMS

1. Explain in your own words how you would measure each of the parameters given in figure 4-2.
2. Make a sketch showing how a piezoelectric cell could be used to measure the acceleration of a rocket.
3. What does "piezo" mean?
4. A certain crystal has a coupling coefficient of 0.32. How much electrical energy must be applied to produce an output of 1 oz-in. of mechanical energy?

experiment 5 STRAIN GAGES

INTRODUCTION. Selecting the most suitable transducer is the initial step in designing an effective instrumentation system. A strain gage is a sensing or detecting element that converts mechanical force, weight or pressure into an electrical signal which provides a readout of the quantity being measured. In this experiment we will investigate the operation of one type of strain gage.

DISCUSSION. The strain gage is a transducer employing electrical resistance variation to sense the strain produced by a force. It is a very versatile detector for measuring weight, pressure, mechanical force, or displacement.

Strain, being a fundamental engineering phenomenon, exists in all matters at all times, due either to external loads or the the weight of the matter itself. These strains vary in magnitude, depending upon the materials and loads involved. Engineers have worked for centuries in an attempt to measure strain accurately, but only in the last decade have we achieved much advancement in the art of strain measurement. The terms *linear deformation* and *strain* are synonymous and refer to the change in any linear dimension of a body, usually due to the application of external forces. The strain of a piece of rubber, when loaded, is ordinarily apparent to the eye. However, the strain of a bridge strut as a locomotive passes may not be apparent to the eye. Strain as defined above is often spoken of as "total strain." Average unit strain is the amount of strain per unit length and has somewhat greater significance than does total strain. Strain gages are used to determine unit strain, and consequently when one refers to strain, he is usually referring to unit strain. As defined, strain has units of inches per inch.

The importance of the measure of strain has been known ever since the seventeenth century, when Hooke pointed out that for many common materials, within certain limits there is a constant ratio between *stress* and strain. *Stress* is defined as *the internal force per unit area.* The constant of proportionality between stress and strain implied in Hooke's Law is known as the *modulus of elasticity* of the material, or Young's Modulus, named after the man who is credited with defining it. Mathematically, this can be expressed as

$$\boxed{E = \frac{S}{\Sigma}} \tag{5.1}$$

where

E = modulus of elasticity in psi

S = stress in psi

Σ = strain in inches/inch

Keeping in mind the relationship between stress and strain, it becomes apparent that we can determine within limits the average intensity of stress in a body under some given external load by measuring the strain and multiplying by the modulus of elasticity for that body. This is basically the only manner in which stress can be determined, since stress is not a fundamental physical quality like strain, but only a derived quantity.

The reason that stress can only be determined within limits is because the stress-strain diagram for a material has a linear

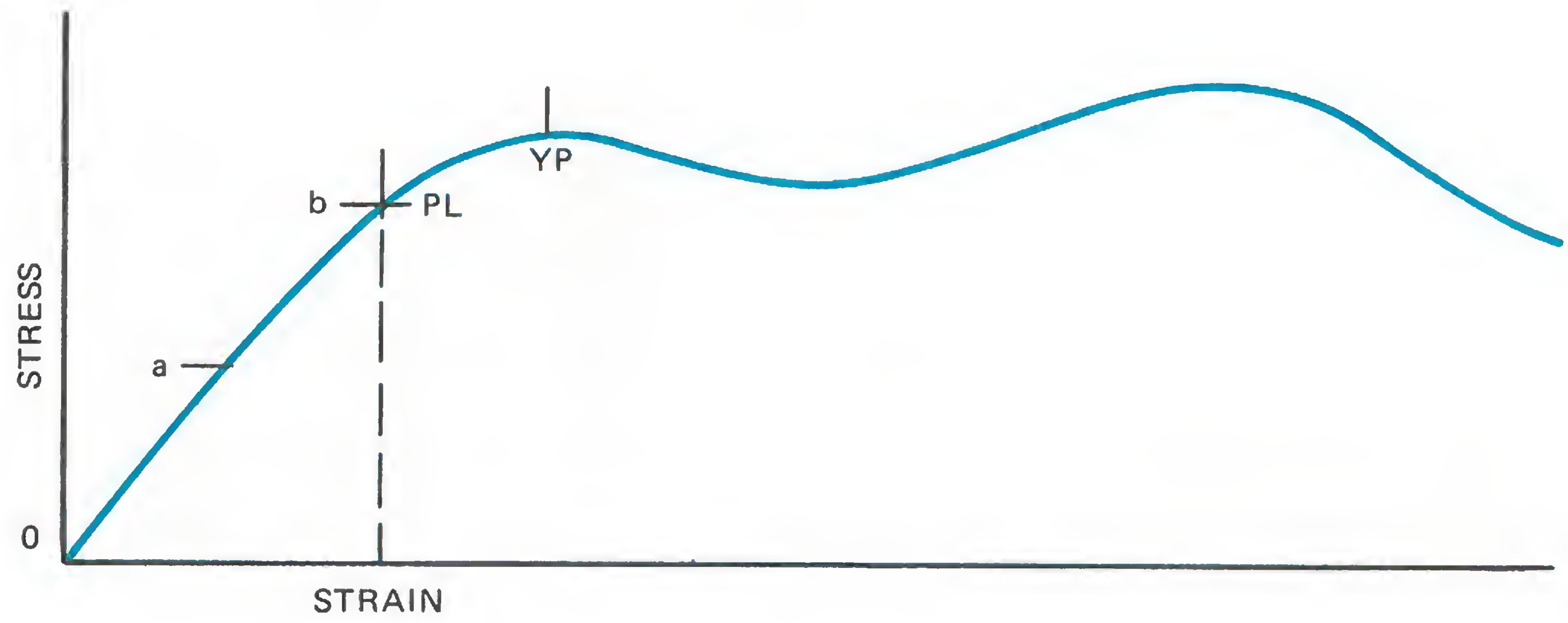


Fig. 5-1 Stress-Strain Diagram for Elastic Metallic Materials

relationship only for the first amount of loading. Figure 5-1 shows a typical stress-strain curve.

If accurate measurements are taken as a piece of metal is stretched in a testing machine, the stress-strain relationship would look about like the graph in figure 5-1. There are a number of important things to be learned from such a plot.

1. The section of the diagram at the beginning is essentially straight, having a constant slope.
2. Above point PL the strain is no longer linearly proportional to the stress. This point PL is called the proportional limit. From this point on, the material is still within the elastic limit and up to point YP the material should return approximately to its original length when the load is removed.
3. YP is the yield point and when it is reached the sample will continue to strain without increased loading.
4. When a material is stretched beyond YP, it will not return to its original length when the load is removed.

Strain gages work on the principle that as a piece of wire is stretched, its resistance changes. A strain gage of either the bonded or the unbonded type is made of fine wire wound back and forth in such a way that with a load applied to the material it is fastened to, the strain gage wire will stretch, increasing its length and decreasing its cross-sectional area. The result will be an increase in its resistance, because the resistance, R, of a metallic conductor varies directly with length, L, and inversely with cross-sectional area, A. Mathematically the relationship is

$$\boxed{R = \frac{KL}{A}} \qquad (5.2)$$

where K is a constant depending upon the type of wire, L is the length of the wire in the same units as K, and A is the cross-sectional area measured in units compatible with K.

Four properties of a strain gage are important to consider when it is used to measure the strain in a material. They are:

1. *Gage configuration.*
2. *Gage sensitivity.*
3. *Gage backing material.*
4. *Method of gage attachment.*

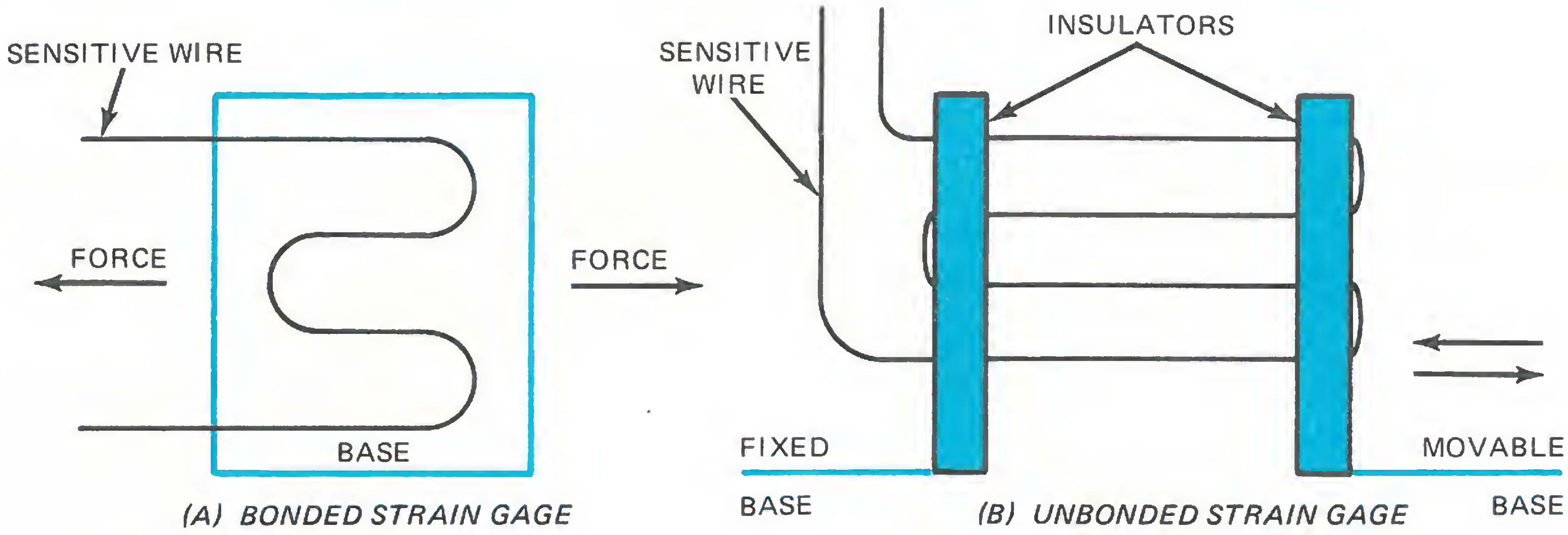


Fig. 5-2 Bonded and Unbonded Strain Gages

Strain gages are divided into two types, (1) bonded and (2) unbonded. Bonded strain gages consist of several loops of fine wire which are cemented to a base of paper or thin plastic. The wire has a diameter of about 0.001 in. and a nominal resistance of about 120 ohms. Since the mechanical strength of the gage must be essentially zero with respect to the sample being tested, the base material is relatively weak. With a good bond between the base and the material being tested, either tensile or compressive strains may be measured.

Unbonded strain gages have the strain-sensitive resistive components mounted on parts which have relative motion with respect to each other. This motion is independent of strain. The wire is applied with an initial tension such that the device can measure both tension and compression. Figure 5-2 shows the two types of strain gage configuration.

The sensitivity of a strain gage is a function of the conductive material, size, configuration, nominal resistance, and the way the gage is energized.

Strain-gage conductor materials may be either metal alloys or semiconductor material. Nickel-chrome-iron- alloys tend to yield high gage sensitivities as well as have long gage life. These alloys are quite good when used for dynamic strain measurements, but because of a high temperature coefficient, they are not as satisfactory for static strain measurements.

Copper-nickel alloys are generally used when temperatures are below 500 to 600°F. They are less sensitive to temperature changes and provide a less sensitive gage factor than the nickel-chrome-iron alloys. Nickel-chrome alloys are useful in the construction of strain gages for high temperature measurements.

The backing material used for a particular strain gage depends on the measurement environment and the gage attachment method. At low temperatures, paper backing is the most often used. Epoxy and phenolic backing are used at higher temperatures with mica and metal backings used in the highest temperature applications. When used in static tests over long periods of time, the durability and creep of the backing material are important factors.

There are two principal methods of attachment used: cementing and welding. Welding is the most straight-forward and reliable attachment method when the test item permits it. There are many cements available for differing gage backing materials

and test environments. These include cellulose nitrate adhesives (model cements), epoxy adhesives, thermoplastic resins, and ceramics. With any one of these adhesives, proper cleansing, careful attachment, and adequate curing procedures are essential.

In using electric strain gages, two physical qualities are of particular interest, the change in gage resistance and the change in length (strain). The relationship between these two variables is dimensionless and is called the "gage factor" of the strain gage and can be expressed mathematically as

$$\boxed{F = \frac{\Delta R/R}{\Delta L/L}} \qquad (5.3)$$

In this relationship R and L represent, respectively, the initial resistance and the initial length of the strain gage wire, while ΔR and ΔL represent the small changes in resistance and length which occur as the gage is strained along with the surface to which it is bonded. The gage factor of a strain gage is a measure of the amount of resistance change for a given strain and is thus an index of the strain sensitivity of the gage. With all other variables remaining the same, the higher the gage factor, the more sensitive the gage and the greater the electrical output.

Since the bonded wire resistance strain gage operates on the principle that the electrical resistance of the gage varies with strain, the gage must be connected to a device capable of detecting small resistance changes. The amount of resistance change in the gage corresponding to a particular load on the piece being tested is the value of ΔR in equation (5.3). The values of R, the *nominal gage resistance,* and F, the gage factor, are known because this information is supplied by the strain gage manufacturer. The only unknown quantity then remaining in the equation is $\Delta L/L$, the unit strain. Equation 5.3 can be rewritten in the form

$$\boxed{\Sigma = \frac{\Delta L}{L} = \frac{\Delta R/R}{F}} \qquad (5.4)$$

Equation 5.4 shows that unit strain equals the unit change in resistance ($\Delta R/R$) divided by the gage factor. The unit strain caused by a particular load is determined by substituting ΔR into equation 5.4 with the known quantities R and F.

All this is a very simple procedure except for one small item. A device is needed for measuring ΔR. ΔR is a very small quantity and could be measured by accurately measuring the initial resistance, R, and the resistance of the gage under loaded conditions, R_1, and subtracting the smaller from the larger. However, R and R_1, whose difference is ΔR, must be accurate to about one-thousandth of one percent. A typical ΔR is 0.008 ohms. Conventional ohmmeters are not capable of measuring resistance with sufficient precision to detect such minute differences. However, with the use of a *Wheatstone Bridge,* ΔR can be measured as illustrated in figure 5-3.

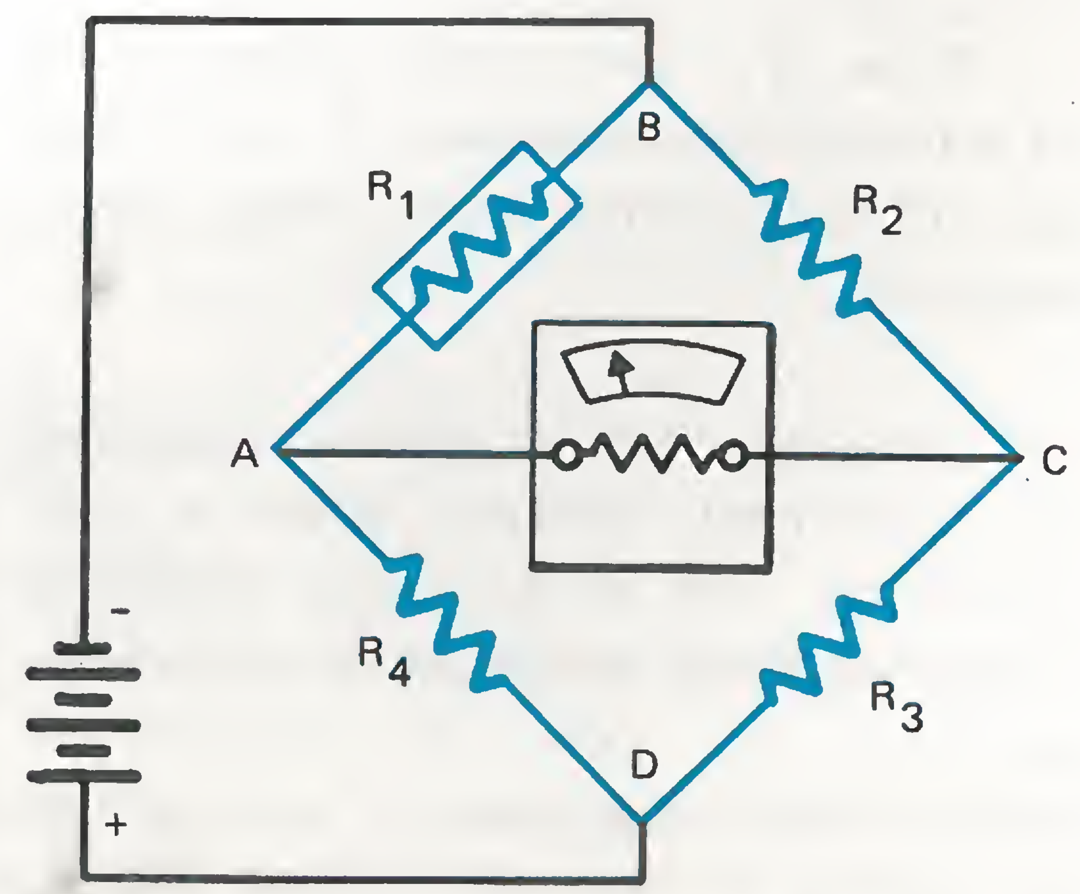


Fig. 5-3 Basic Wheatstone-Bridge Circuit

In this schematic assume that R_1 is the resistance of the strain gage, R_2 and R_3 are ratio arms, and R_4 is a resistance whose value is precisely known. It can be shown that, when resistance values in this circuit are such that no current flows through the galvanometer, then R_1 is to R_4 as R_2 is to R_3. That is

$$\boxed{\frac{R_1}{R_4} = \frac{R_2}{R_3}} \qquad \textbf{(5.5)}$$

From this,

$$R_1 = \frac{R_2}{R_3} R_4$$

When the load changes the resistance R_1 by some value ΔR, the needle of the galvanometer will deflect because the bridge is no longer balanced. To bring the bridge back into balance, the ratio of R_2 to R_3 is changed. The new ratio times R_4, the known resistance, must equal $R_1 + \Delta R_1$. Equation 5.6 gives this relationship.

$$R_1 + \Delta R_1 = \frac{R_2'}{R_3'} R_4 \qquad \textbf{(5.6)}$$

Since R_1 was known before loading, ΔR is the difference between R_1 and the valve read from the Wheatstone Bridge after rebalancing.

Even though static strain is examined in this experiment, dynamic strain is also of importance. The term dynamic strain is used to describe strain which varies appreciably in magnitude over short time intervals. It is obvious that if the strain in some structure was varying at more than several cycles per minute, it would be difficult or actually impossible to determine the strain by the process of balancing the bridge. There are numerous factors which contribute to the difficulty of accurately determining dynamic strains. Most of these are related to the fact that, generally, no two successive dynamic tests will produce identical results. Figure 5-4 shows idealized types of static and dynamic strain.

Figure 5-4A represents static strain which varies slowly or not at all. This is the type of strain examined in this experiment.

Figure 5-4B represents a pure oscillatory dynamic strain. In other words, the strain is varying positive to negative (tension to compression) values of equal magnitude. Figure 5-4C results when figure 5-4A and B are superimposed. It also represents a static

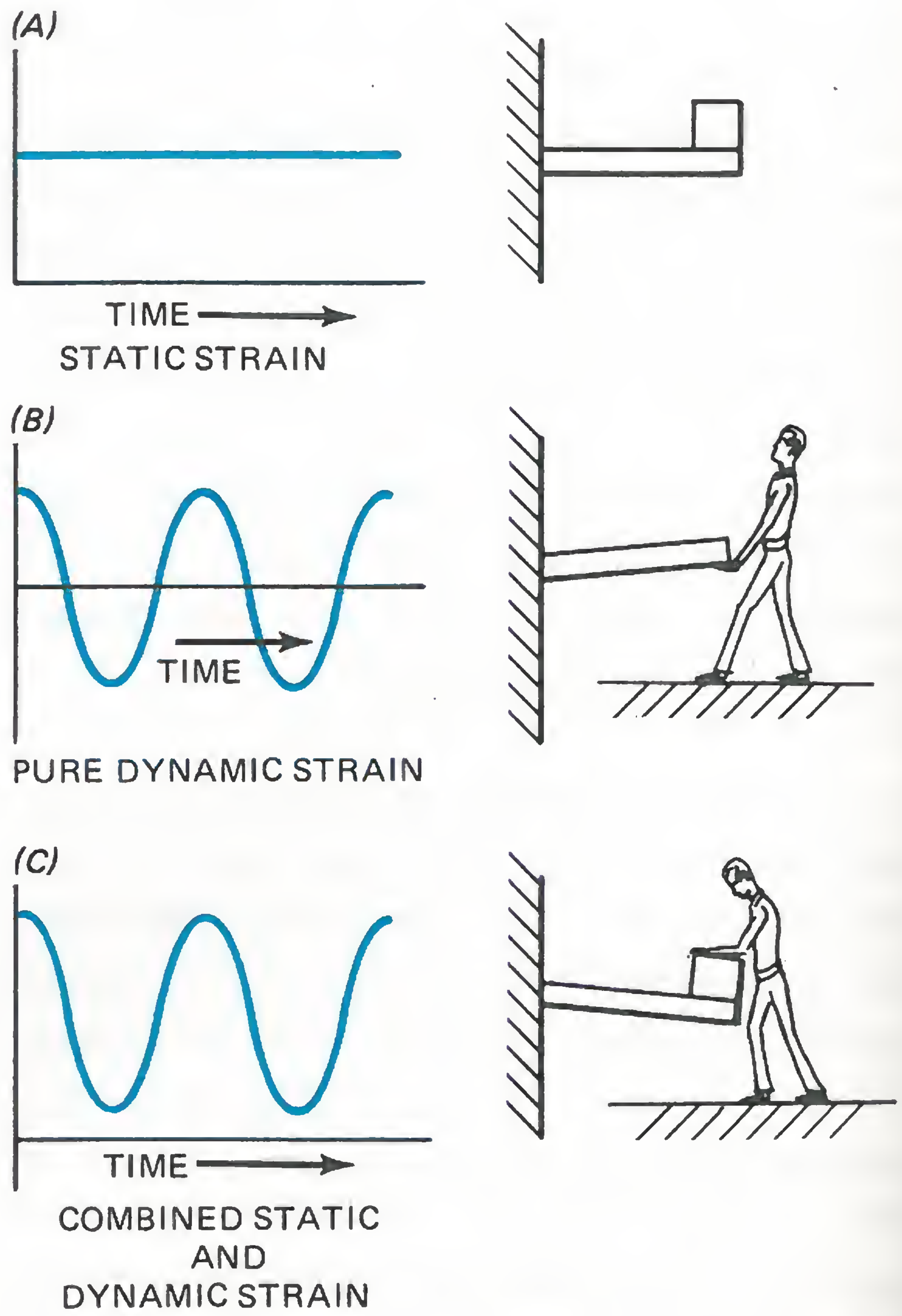


Fig. 5-4 Idealized Types of Static and Dynamic Strain

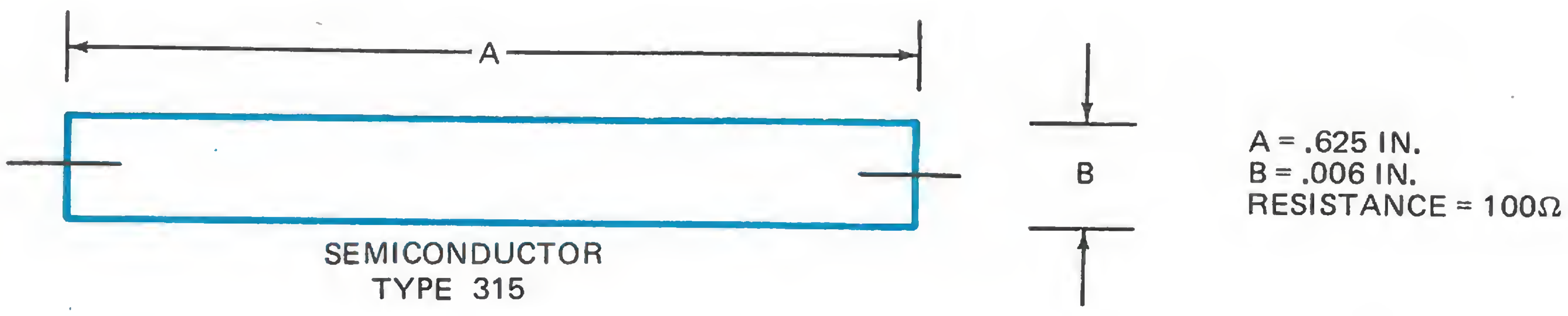


Fig. 5-5 A Semiconductor Strain Gage

strain which is modulated by a dynamic component. Dynamic strain is very important and the technician should be aquainted with it, though it will not be investigated in this experiment.

Strain gage sensitivity has been improved by using semiconductors. The flexible silicon strain gage is very practical because it is as stable as the metallic type and has a higher output level. This type of strain gage can detect microinches of change in length per inch of length. Figure 5-5 shows a semiconductor element used in a microstrain system.

MATERIALS

1 Aluminum bar stock 1/8 in. X 4 in. X 21 in. E = 10,000,000
1 Steel bar stock 1/8 in. X 2 1/2 in. X 20 in. E = 30,000,000
1 Wheatstone Bridge
2 Strain gages F = 1.98 ± 1%
  R = 119.6 ± 0.2 ohms
1 C-Clamp
  Weights 0-15 lbs as needed
  Adhesive for mounting gages

PROCEDURE

1. Attach the strain gages to the bar stock approximately one inch from one end with the glue provided.
2. Clamp the steel bar to a table and connect the leads of the strain gage to the Wheatstone Bridge as shown in figure 5-6.

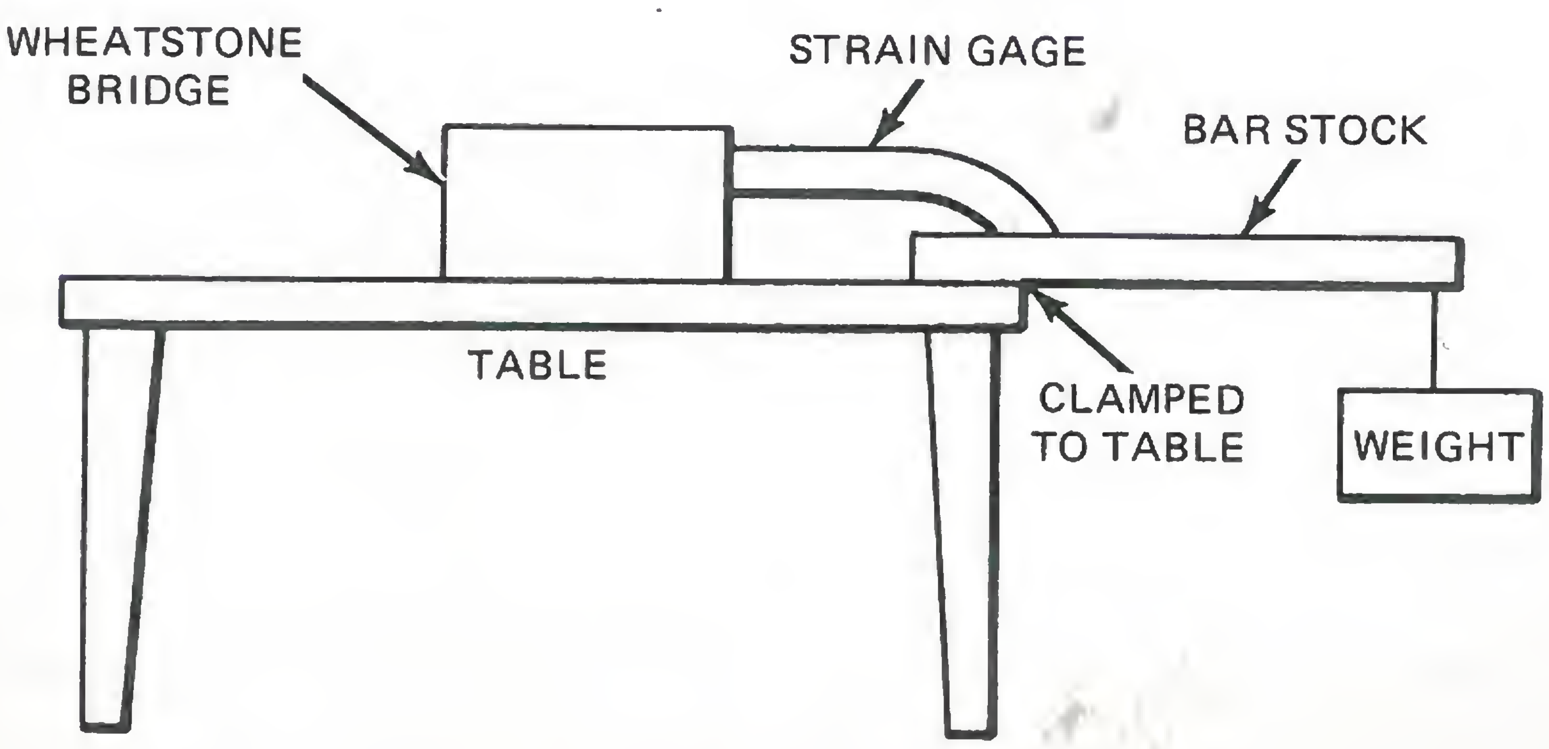


Fig. 5-6 Strain Gage Application

3. Balance circuit with no weight on the bar.
4. Add weight in small increments at the end of the bar stock that is not clamped until ΔR is 0.1Ω.
5. Record the value of weight used and the resistance measured with the bridge in the data table, figure 5-7.
6. Add more weight ultil ΔR is equal to 0.2Ω. Record the weight and resistance in the table.
7. Repeat step 6 until ΔR is equal to 0.3Ω.
8. Replace the steel bar with the aluminum bar.
9. Repeat the experiment using the aluminum bar.
10. Calculate $\frac{\Delta L}{L}$ for each amount of weight using equation 5.4.
11. Calcualte the stress using equation 5.1.

	For Steel				For Aluminum			
Weight	0				0			
Resistance								
ΔR					0			
Strain $\frac{\Delta L}{L}$ Micro in/inch					0			
Stress (psi)					0			

Fig. 5-7 The Data Table

ANALYSIS GUIDE. Explain what is meant by dynamic strain, static strain, and modulus of elasticity. Explain the reason for using very small wire on the strain gage. Give a practical application of a strain gage to the automotive industry. Plot graphs of resistance versus weight, stress versus strain and resistance versus strain for both the steel and the aluminum bar.

PROBLEMS

1. A round steel bar, 2" in diameter and 40" long, is subject to a tensile force of 33,000 lbs. How much does it stretch? Use the equation $e = \frac{F\ell}{AE}$ where e is the deformation, F is the force, ℓ is the original length, A is the cross-sectional area and E is the modulus of elasticity.

2. What is the strain in an aluminum bar which is subjected to a compressive stress, S, of 9,000 psi?

3. The general equation applicable to the resistance of a strain gage is

$$\Sigma = \frac{\Delta R}{FR}$$

Given this equation and F = 2.0, R = 130 and Σ of one microinch/inch, what change in resistance must be measured for the above data? Can an ordinary ohmmeter measure this change?

experiment 6 *VARIABLE INDUCTANCE TRANSDUCER*

INTRODUCTION. In many applications of machine motion the linear displacement of some parts of the machine are important. In this experiment we will examine a method of measuring displacement using a variable inductance transducer.

DISCUSSION. Displacement and pressure are two variables that can be measured directly by the use of an iron core inductor with a constant AC input signal. A coil operating on a fixed frequency has only one unknown variable and that is its magnetic circuit. In contrast to air, which is a relatively poor carrier of magnetic flux, iron and some iron alloys are exceedingly good conductors of magnetic flux. Some are as much as 200,000 times better than air. Consequently, when iron is used as the core of an inductor, the result will be a greater voltage of self-induction. The voltage that is self-induced in the circuit will be

$$\boxed{e = L\frac{di}{dt}} \tag{6.1}$$

where

e = voltage across the coil

L = the inductance in Henrys

$\frac{di}{dt}$ = rate at which the current changes in amperes per second

If $i_1 = i_2$ the induced voltage e_2 would be much greater than e_1 because of the greater flux of L_2.

If two inductors are connected in series, as shown in figure 6-2, the induced voltage is additive, and according to Kirchoff's voltage law,

$$e_t = e_1 + e_2 \tag{6.2}$$

Using equation 6.1, e_1 and e_2 can be determined as

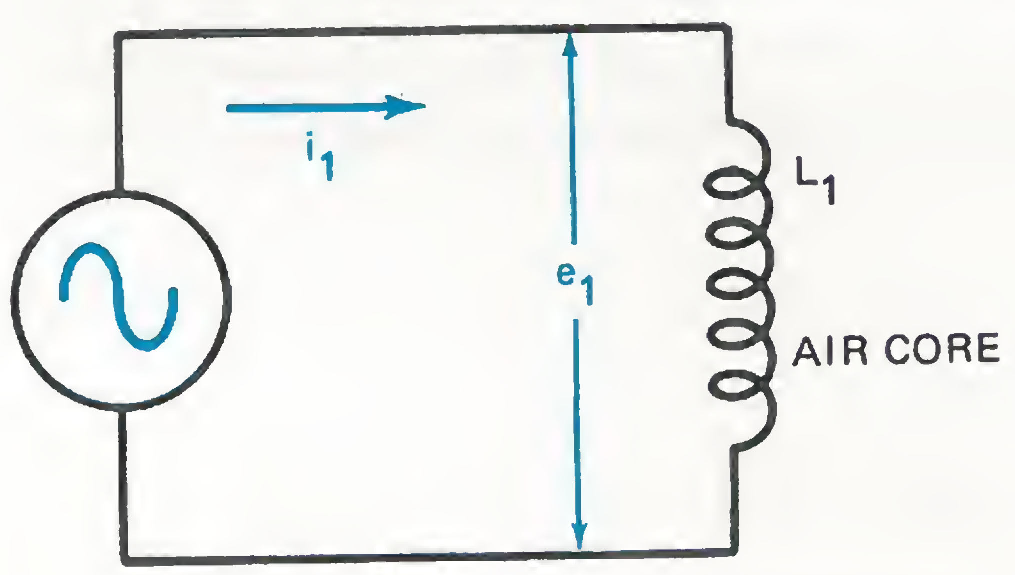
$$e_1 = L_1\frac{di}{dt} \text{ and } e_2 = L_2\frac{di}{dt}$$

Substituting these expressions into equation 6.2 gives us

$$e_t = L_1\frac{di}{dt} + L_2\frac{di}{dt}$$

or

$$e_t = \frac{di}{dt}(L_1 + L_2) \tag{6.3}$$



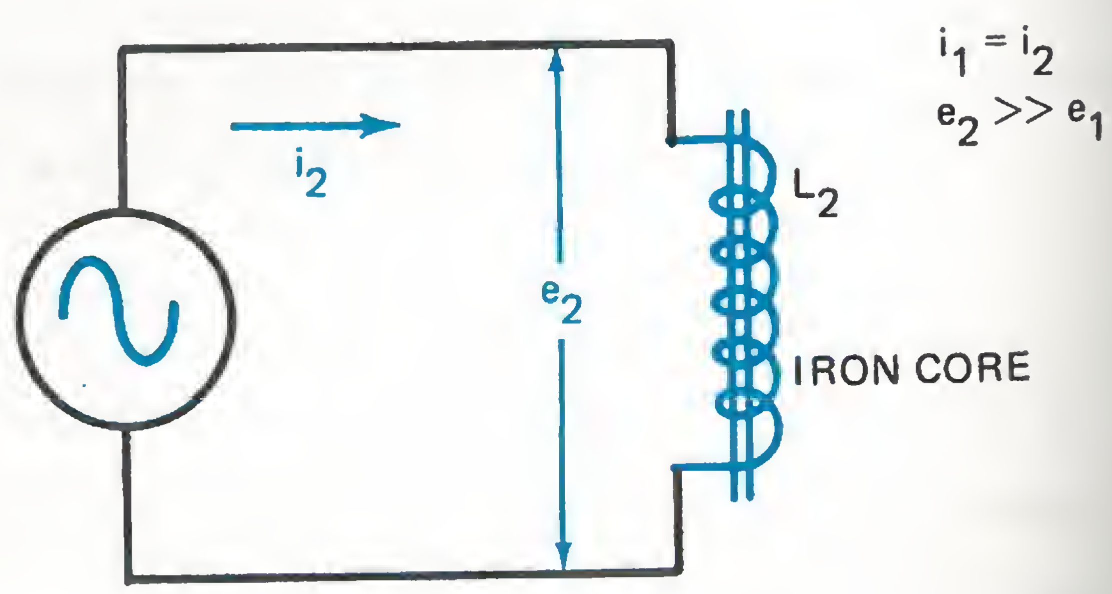


Fig. 6-1 Two Inductors Producing an Induced Voltage

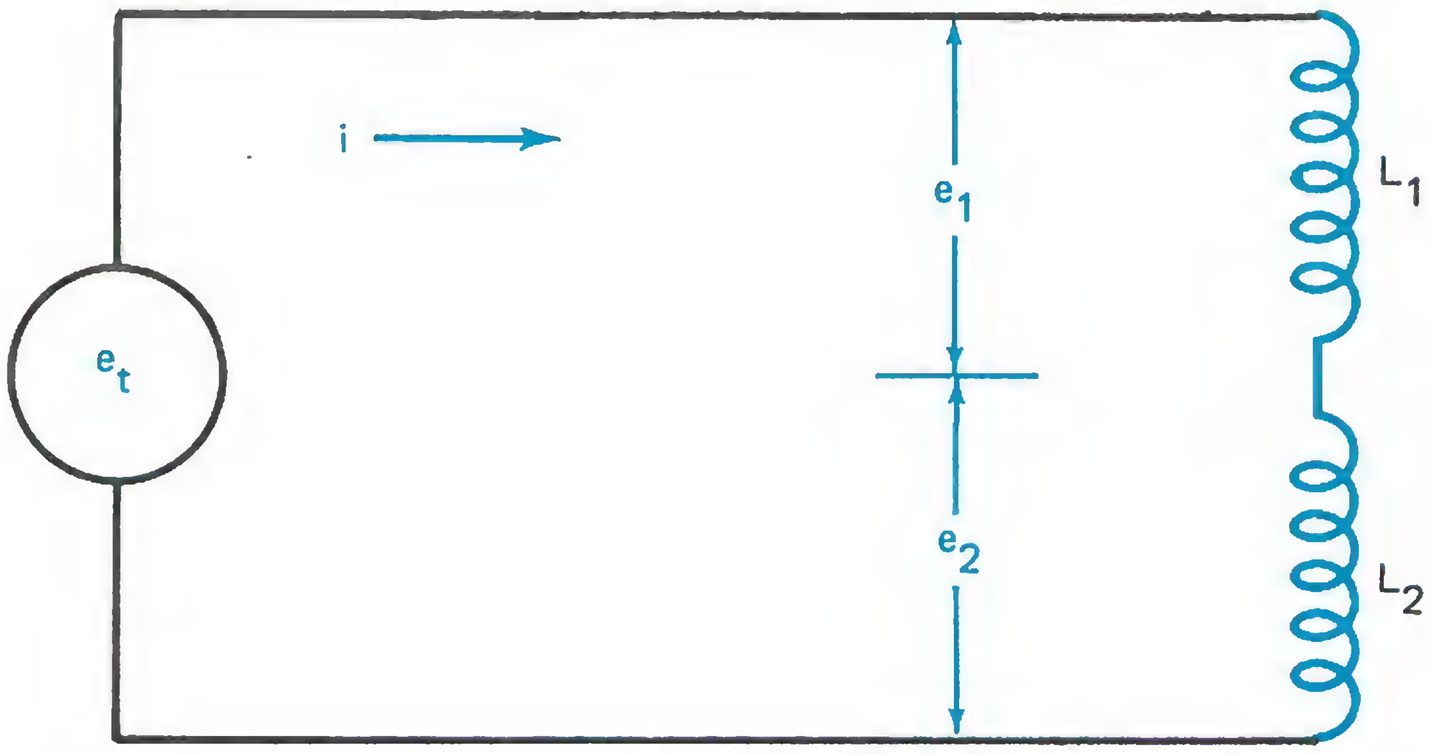


Fig. 6-2 Two Inductors in Series

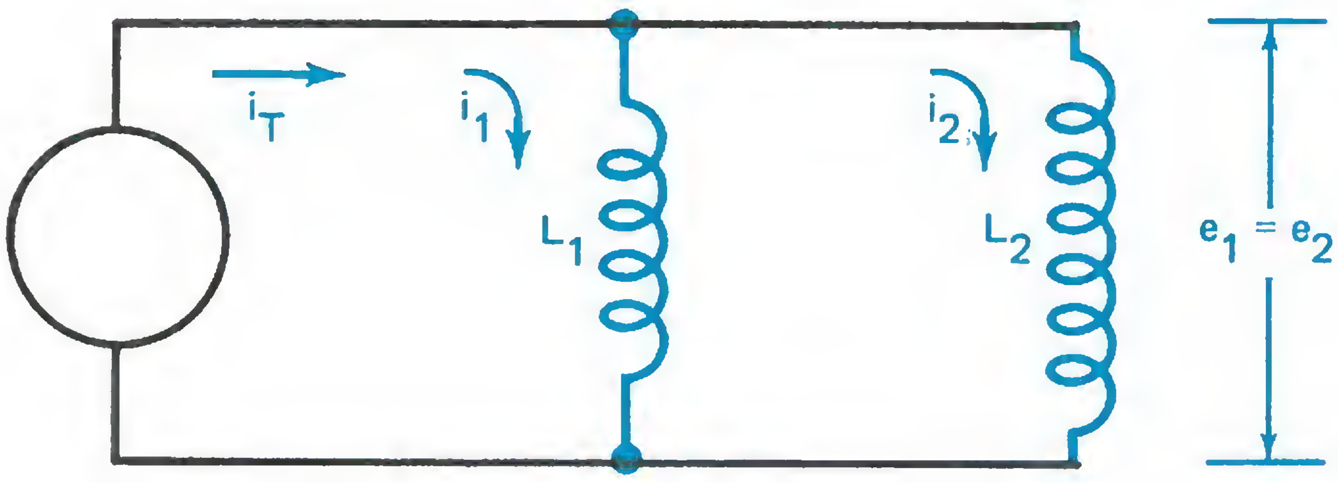


Fig. 6-3 Two Inductors in Parallel

From equation 6.3 we see that L_1 and L_2 are additive. That is,

$$\boxed{L_T = L_1 + L_2} \tag{6.4}$$

If two inductors are placed in parallel as shown in figure 6-3 the induced voltages are equal and from Kirchoff's current law

$$i_t = i_1 + i_2 \tag{6.5}$$

If i_t changes with time, so must i_1 and i_2. Therefore, differentiating 6.5 with respect to time gives

$$\frac{di}{dt} = \frac{di_1}{dt} + \frac{di_2}{dt} \tag{6.6}$$

From equation 6.1,

$$\frac{di}{dt} = \frac{e}{L}$$

Substituting $\frac{e}{L}$ into equation 6.6 gives us

$$\frac{e_t}{L_t} = \frac{e_1}{L_1} + \frac{e_t}{L_2} \tag{6.7}$$

Because the supply voltage e_t is equally available to each inductor, equation 6.7 reduces to

$$\frac{e_t}{L_t} = \frac{e_t}{L_1} + \frac{e_t}{L_2}$$

or

$$\boxed{\frac{1}{L_t} = \frac{1}{L_1} + \frac{1}{L_2}} \tag{6.8}$$

From equation 6.4 and 6.8 we see that inductors in series and parallel have additive characteristics similar to resistors in series and parallel.

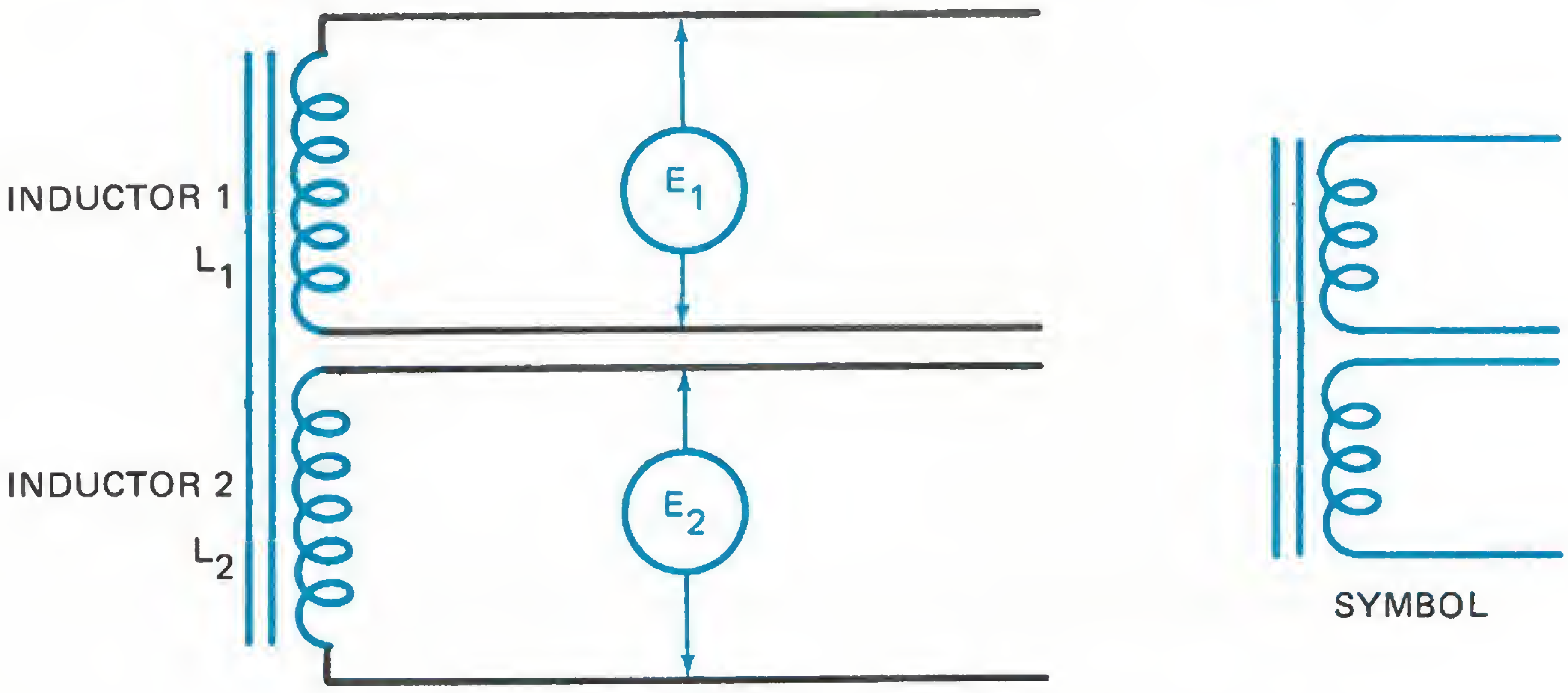


Fig. 6-4 Two Inductors With Coupling

Now suppose that two inductors are placed close together as shown in figure 6-4 with an iron cone through them. This is known as mutual coupling, and is defined as the transfer of energy from one circuit to another by magnetic coupling. Unity or 100 percent coupling exists when all of the magnetic flux lines of one inductor cuts through the other inductor. As already pointed out, when there is no mutual coupling between inductors in **series**, the total inductance is the sum of the individual inductances:

$$\boxed{L_T = L_1 + L_2 + L_3 + \ldots}$$

When there is no mutual coupling between inductors in **parallel**, the total inductance is

$$\boxed{L_T = \frac{1}{1/L_1 + 1/L_2 + 1/L_3 + \ldots}}$$

However, when coils are placed in such a way that coupling does exist, the total inductance depends on whether the individual fields aid or oppose each other. Two coils that are aiding each other are wound such that the current is flowing through them in the same direction as shown in figure 6-5 (A).

The total inductance of two coils that

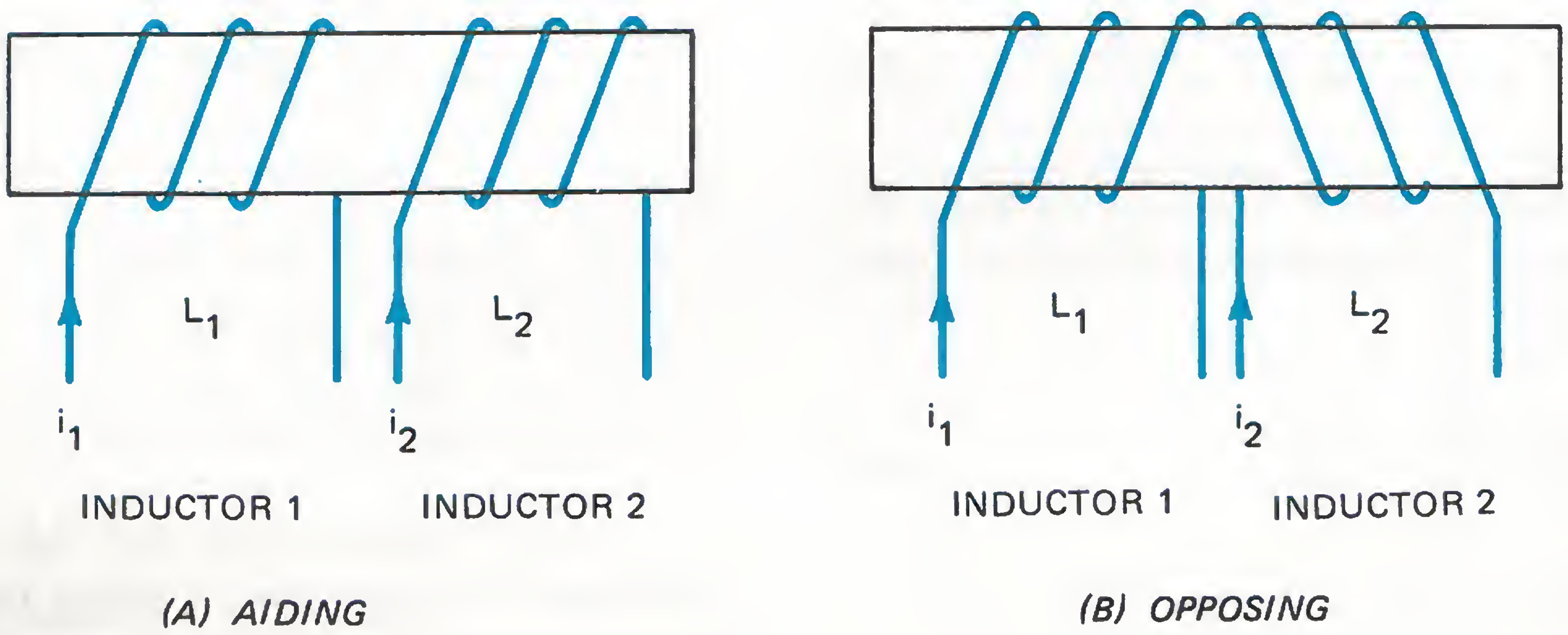


Fig. 6-5 Aiding and Opposing Inductors

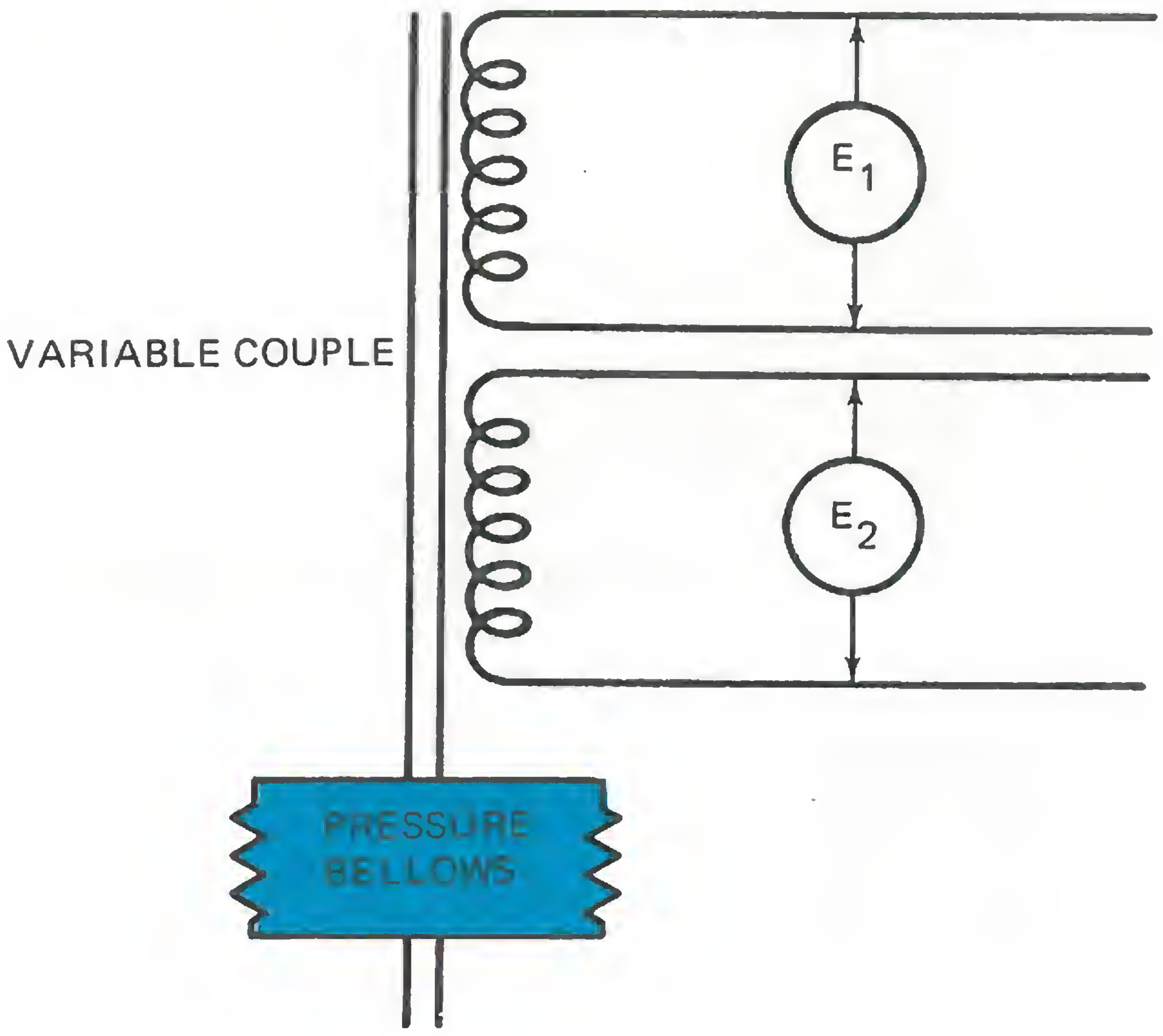


Fig. 6-6 Variable-Inductance, Pressure-Actuated, Pressure-Current Transducer

aid each other is

$$\boxed{L_T = L_1 + L_2 + 2M} \qquad (6.9)$$

where M is

$$\boxed{M = K\sqrt{L_1 L_2}}$$

and K is the coefficient of coupling between the windings.

Two coils that are opposing each other are wound such that the current in each is flowing in opposite directions as shown in figure 6-5b.

The total inductance of two coils that oppose each other is given by

$$\boxed{L_T = L_1 + L_2 - 2M} \qquad (6.10)$$

Combining equations 6.9 and 6.10 will give a general equation for two coils in series which are mutually coupled:

$$\boxed{L_T = L_1 + L_2 \pm 2M}$$

If it is desired to vary the output of an inductor by some external means, one may connect an apparatus (pressure bellows, mechanical cams, etc.) onto the iron core and alter the induced output voltage as illustrated in figure 6-6.

As pointed out earlier, the more iron placed in the coil, the more self-induced voltage that is produced. As the voltage of self-induction increases, the difference between the applied voltage and induced voltage decreases, and the current decreases proportionally, approaching, but never reaching, zero.

We can conclude, therefore, that as a magnetic material is placed in a coil, more flux will link the windings. As the flux increases, a greater voltage of self-induction will be produced thereby reducing the current. If the coil has a fixed voltage across it, the position of the core will have a great effect on the current. From this, we see that the core position and the current have a definite correlation.

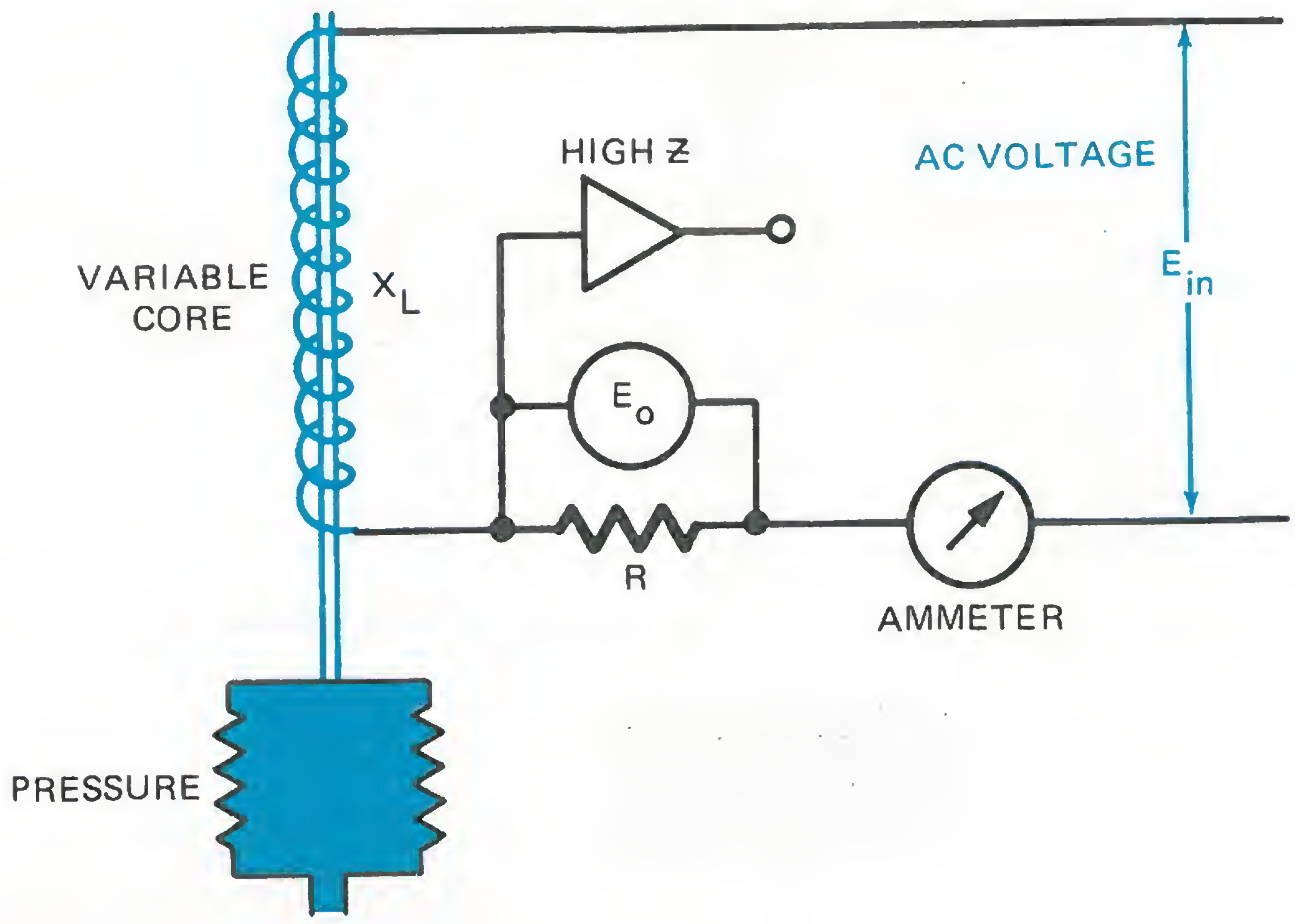


Fig. 6-7 Variable Inductance Transducer

If an alternating voltage E_{in} is applied as shown in figure 6-7, the voltage across the coil will be

$$\boxed{E_o = E_{in} \frac{R}{\sqrt{R^2 + X_L{}^2}}} \tag{6.11}$$

where

E_o = Output voltage
E_{in} = Input voltage
R = Series resistance
X_L = Coil reactance

ΔE_o for a given *impedance* change (ΔZ) is what is important in this experiment. To change this impedance, the input frequency or the inductance could be varied. If the inductor's core is connected to a pressure bellows, as shown in figure 6-7, the output voltage E_o will change proportionally with the length of the core cutting the magnetic lines of force. By changing the frequency, E_o will also change as shown in figure 6-8.

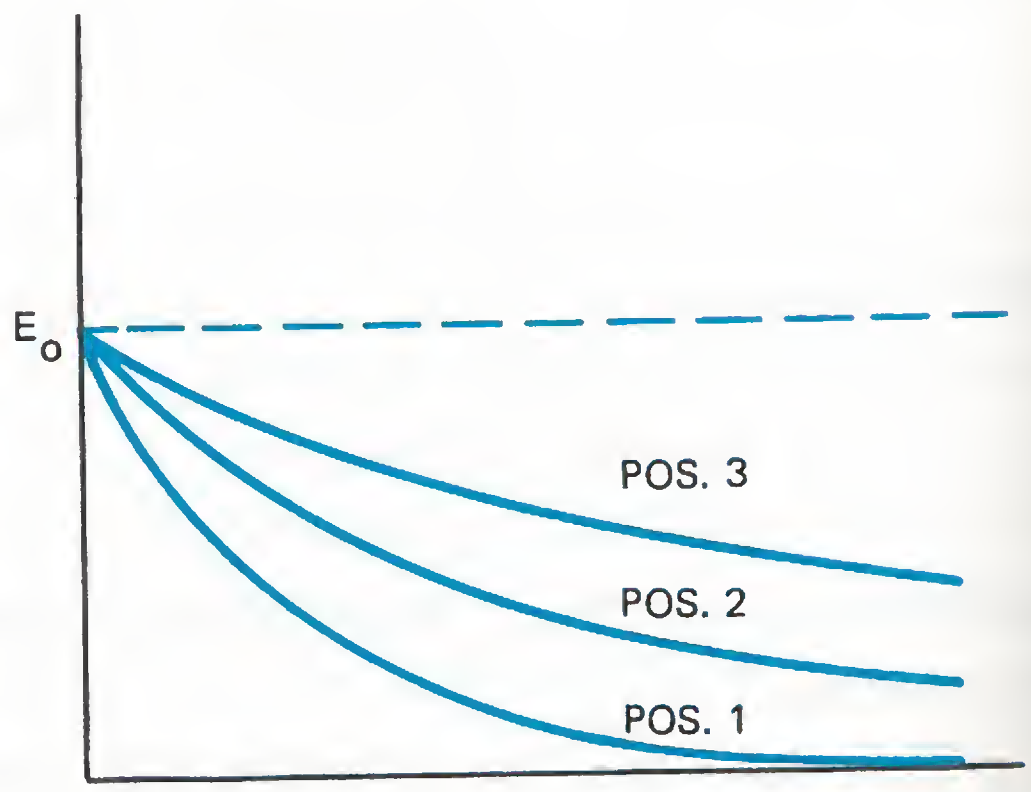


Fig. 6-8 Voltage Versus Frequency for a Given Core Position

Using the principle that the current depends on the position of the core material, a transducer converting mechanical displacement or pressure can be built. If the current output has been calibrated for a certain pressure or displacement, then these values can be read directly from a corresponding meter. If the core material is riding on a cam which is affected by some moving part, the output reading would give the distance the mechanical part moves from a preset position.

The pressure which changes the bellow's positioning moves the core material in and out of the coil. The output reading would represent the pressure change in the system.

MATERIALS

1 Oscilloscope
1 Audio generator
1 100Ω resistor
1 Spring balance
1 Inductor with movable core

PROCEDURE

1. Remove the core of the inductor and mark with a pencil from 0 to 1 inch in 1/4 in. increments.
2. Set up the circuit shown in figure 6-9.

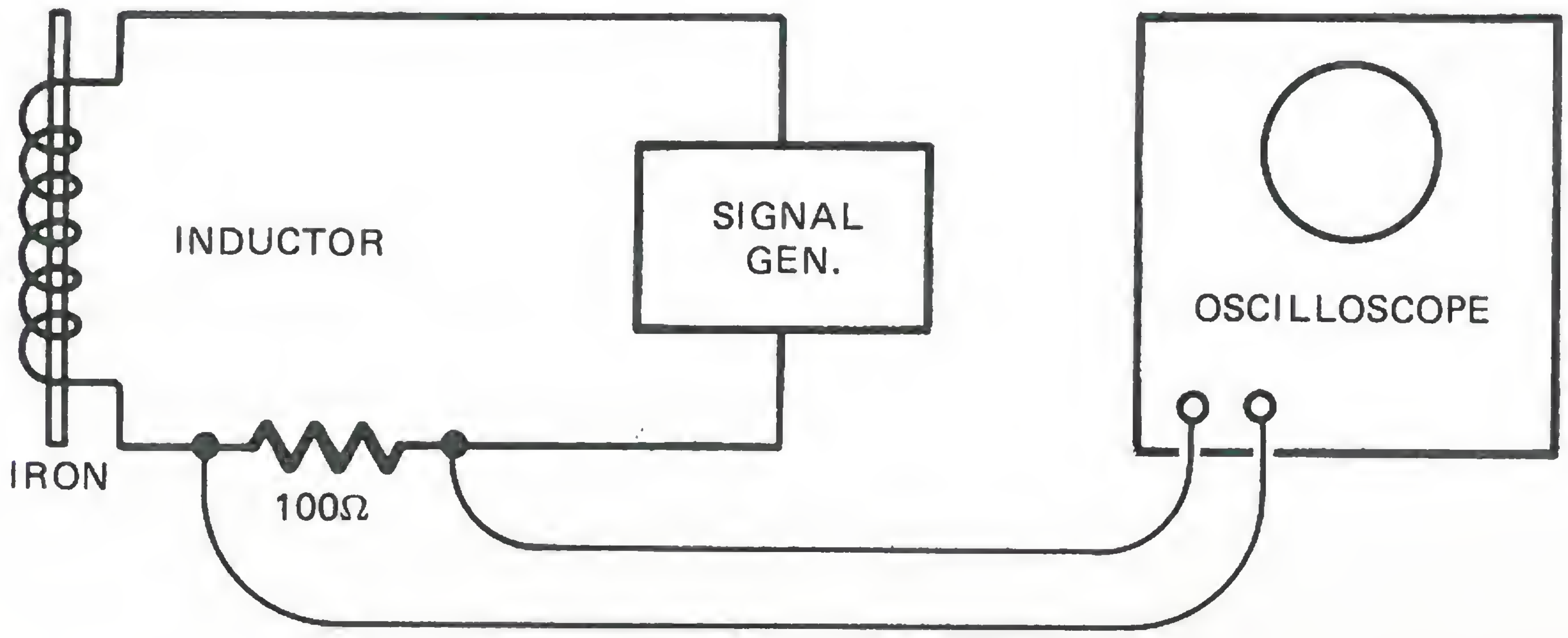


Fig. 6-9 Experimental Circuit

3. Set the output of the signal generator to 2 kHz.
4. With the core all the way in the coil, record the voltage across the 100Ω resistor in the data table. **Note: At this high frequency read the voltage with the oscilloscope.**
5. Change the output to 4 kHz and record the voltage.
6. Record the voltages produced at 6, 8, and 10 kHz.
7. Pull the core out to the 1/4 in. mark.
8. Repeat steps 4, 5, and 6.
9. Repeat the experiment for 1/2, 3/4, and 1 in. increments.
10. Attach one end of the spring balance to the movable core and secure the other end.
11. Set the output of the signal generator to 2 kHz.
12. Push the core into the coil until 8 oz is indicated on the spring balance.
13. Record the voltage.

14. Repeat this part of the experiment for each 8 oz of force until the core is all the way in.
15. From the voltages recorded in the table, calculate the currents.

		2 kHz	4 kHz	6 kHz	8 kHz	10 kHz
0 in.	Voltage Current					
1/4 in.	Voltage Current					
1/2 in.	Voltage Current					
3/4 in.	Voltage Current					
1 in.	Voltage Current					

Force	0 oz	8 oz	16 oz	24 oz	32 oz	40 oz	48 oz	50 oz	64 oz
Voltage									

Fig. 6-10 The Data Tables

ANALYSIS GUIDE. Plot the current versus the frequency for each displacement on a single sheet of graph paper. Also plot the force versus the voltage. Explain how the force-voltage relationship could be used in industry. Explain how a variable inductor transducer could be calibrated to indicate displacement of a moving part.

PROBLEMS

1. With a 1 Henry inductor, a resistance of 100 ohms, E_{in} of 10 volts and a frequency of 5 kHz, calculate the E_o.
2. With an E_o of 10 millivolts, R of 1000 ohms, E_{in} of 10 volts and a frequency of 320 Hz, what is the inductance in Henrys?
3. For two 2H inductors that are mutually coupled, with a coefficient of coupling of 0.83, find the mutual inductance.

experiment **7** *GAGE AND ABSOLUTE PRESSURE RECORDERS*

INTRODUCTION. One of the most common industrial measurement made is that of pressure. In this experiment we will investigate how pressure instruments can be calibrated.

DISCUSSION. When a force is acting perpendicular to a surface which has an area, A, the pressure exerted on the surface is

$$P = \frac{F}{A} \qquad (7.1)$$

where

P = pressure in $lbs/in.^2$
F = force in lbs
A = area in sq. in.

Pressure is always perpendicular to the surface it is acting on and is usually referred to as acting normal to the surface.

Pressure is used with fluid measurement because fluids flow under stress instead of being deformed elastically as solids are. Three characteristics of fluids result from this lack of rigidity: (1) *The forces a fluid exerts on the walls of its container always act perpendicular to the walls,* (2) *An external pressure exerted on a contained fluid is transmitted uniformly throughout the volume of the fluid,* (3) *At any point in a fluid the pressure is the same in all directions.*

Pressure may be measured in a number of ways. The most common methods are with the use of manometers, aneroids, and Bourdon tubes. A manometer measures pressure in terms of the difference in height of two columns of liquid (usually mercury) as shown in figure 7-1A.

Figure 7-1B shows an aneroid which measures pressure in terms of the amount by which the thin, flexible ends of the evacuated chamber move in and out due to external pressure. A Bourdon tube works on the principle that the tube will tend to straighten out when the internal pressure becomes greater than the external pressure.

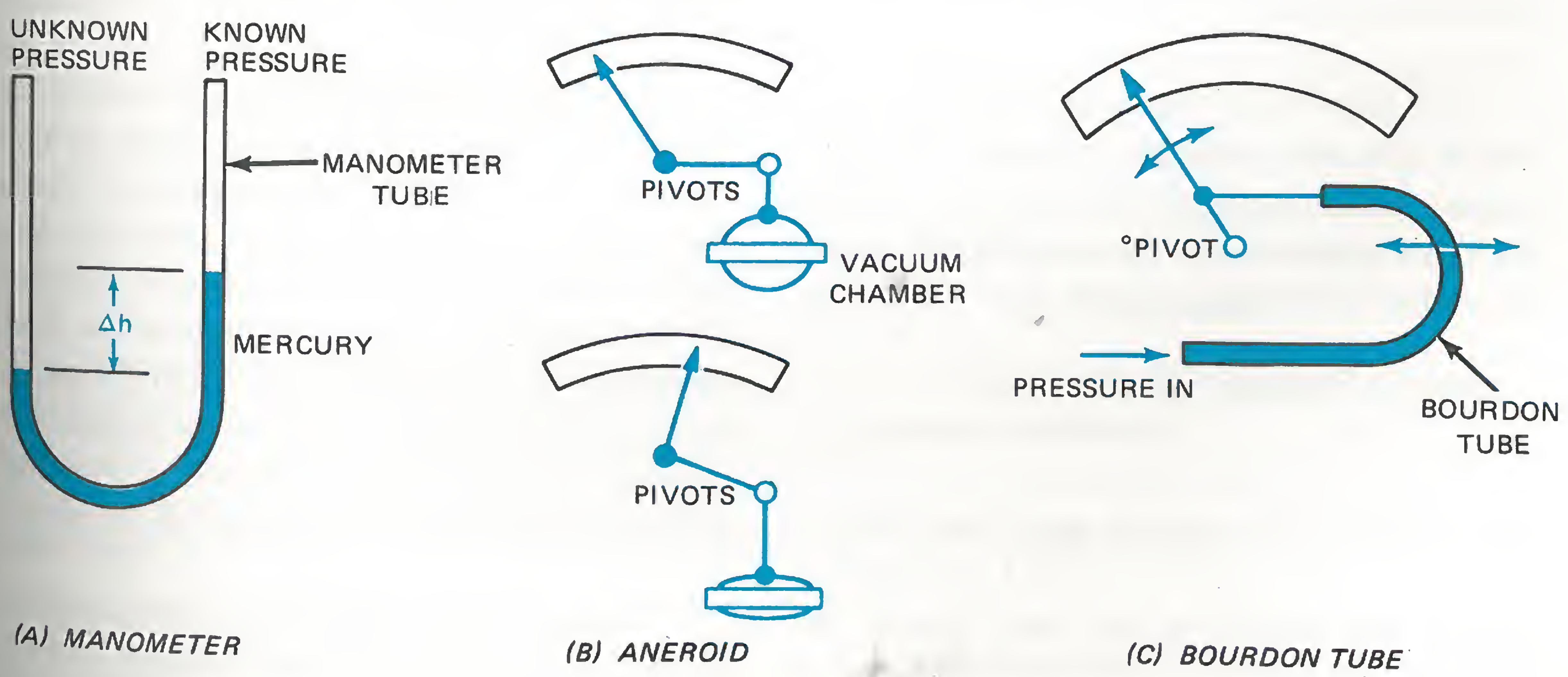


Fig. 7-1 Types of Pressure Gages

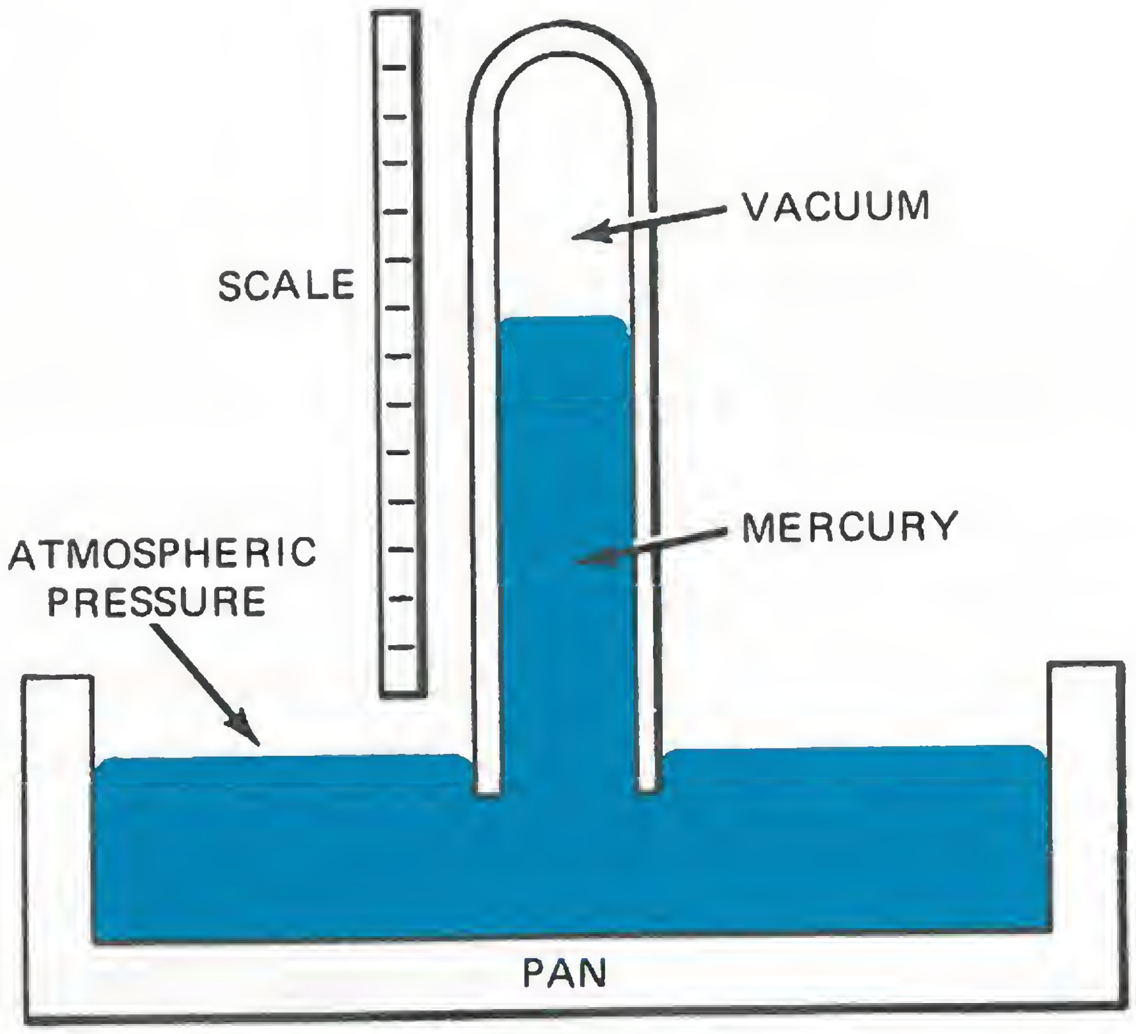


Fig. 7-2 Simple Barometer

Before covering these three methods, as well as other methods of pressure measurement, the three types of pressure scales will be discussed.

The three scales used with pressure measurement are gage pressure, absolute pressure, and the vacuum scales. The difference between the gage pressure scale and the absolute pressure scale is that the location of the zero point on one is not equal to the zero point on the other.

The absolute pressure scale actually represents the true pressure, whereas the gage pressure scale represents the difference in an unknown pressure and the atmospheric pressure. This relationship is given by:

Absolute Pressure = gage pressure + atmospheric pressure

Thus, when a tire pressure gage reads 32 psi, it actually has a pressure of 46.7 psi because atmospheric pressure at sea level is equal to 14.7 psi. At a 5000-foot elevation the atmospheric pressure is 12.2 psi and drops to 9.7 psi at a 10,000-foot elevation.

Atmospheric pressure is measured with a barometer. The simplest barometer consists of a long glass tube which is sealed at one end. The open end (filled with mercury) is placed in a pan of mercury. The mercury falls to a height corresponding to the pressure of the atmosphere and leaves a vacuum above it in the tube. The height of the mercury in the tube moves up and down as atmospheric pressure changes and the level corresponds to the atmospheric pressure in inches exerted on the mercury in the pan.

The gage pressure scale is mounted on a device to measure the pressure above atmospheric. Since all the components are at atmospheric pressure, the zero point on the scale corresponds to the atmospheric pressure at that altitude. Whatever pressures are then read from the scale correspond to the pressure built up above atmospheric. Gage pressure is usually indicated by a small letter g after the pounds-per-square inch readings; i.e., 32 psig.

Vacuum measurement is the measurement of pressures below atmospheric. A vacuum scale is usually graduated in inches of mercury or inches of water. Elastic deforma-

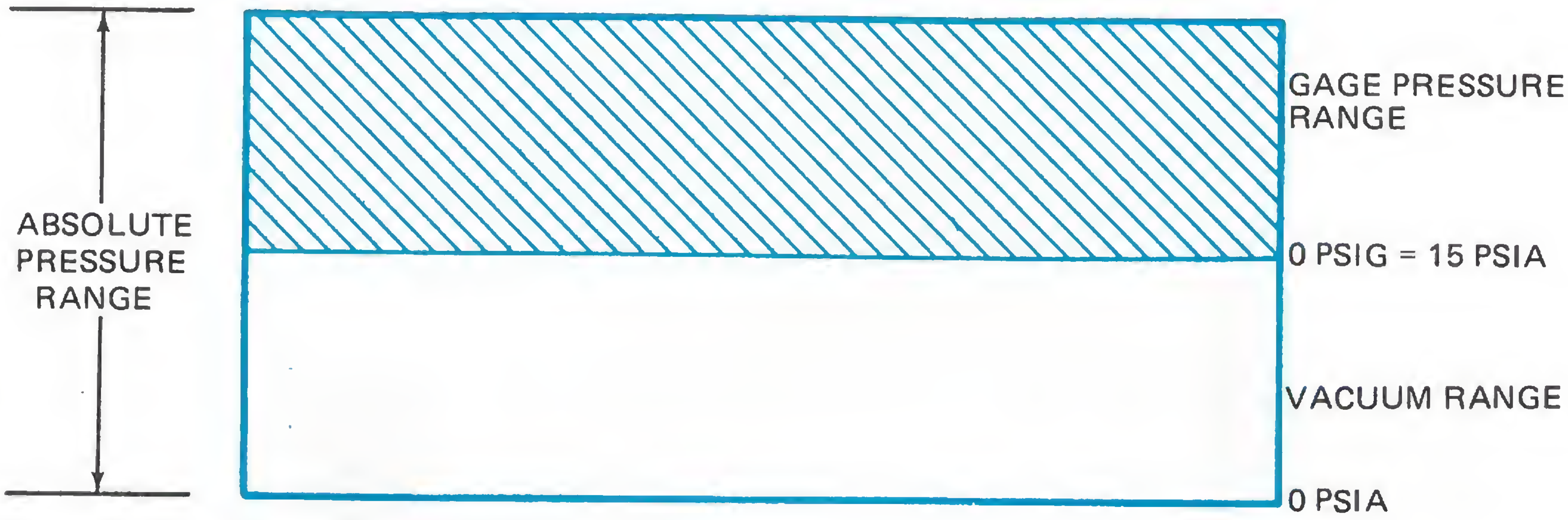


Fig. 7-3 Relationship Between the Pressure Scales

tion elements, such as the Bourdon tube, bellows and diaphragm, are used to measure pressures.

Figure 7-3 shows the relationship between the pressure scales.

The absolute pressure scale includes the gage pressure scale and the vacuum scale. Thus, a pressure of 10 inches of mercury absolute may also be expressed as vacuum of 20 inches of mercury or a gage pressure of -20 inches of mercury. Absolute pressure is distinguished from gage pressure by indicating it psia.

Because forces cannot be seen, only the results of a force can be used as a measure of it. Forces move, accelerate, bend, distort, and otherwise change an object. The application of any force, or pressure, will always produce a deflection, a distortion, or some change in volume, no matter how small or large the force.

The range of practical pressure instruments is quite large. The construction of a particular gage depends upon the pressure range. There are both mechanical and electrical type pressure measuring devices, all of which can be considered transducers in that they change one form of energy into another form. A few of these instruments will be discussed.

The liquid-filled manometer is one of the most useful and accurate instruments for measuring any variable that is a function of pressure. Because of its simplicity and accuracy, the manometer is widely used. The U-tube manometer can be filled about halfway with distilled water, oil, mercury, or any other liquid which flows easily. For low pressure or vacuum ranges, water or oil is frequently used as the liquid. The density of such liquid is very low compared with mercury and, therefore, the liquids are more sensitive to slight changes in pressure. For higher pressure ranges, mercury is most often used.

When no pressure is applied to either tube of the manometer, the liquid remains at the zero reading on the scale where both levels are equal. When a pressure, P, is applied to the left tube, the manometer liquid is pushed down in the left side and up in the right side until equilibrium or static conditions are achieved. This occurs when

$$P = hw_m$$

where

h = the height difference in the liquid levels

w_m = weight density of the liquid

Accuracy is not affected by the shape or size of the tube. The difference between the levels will always be the same for the same

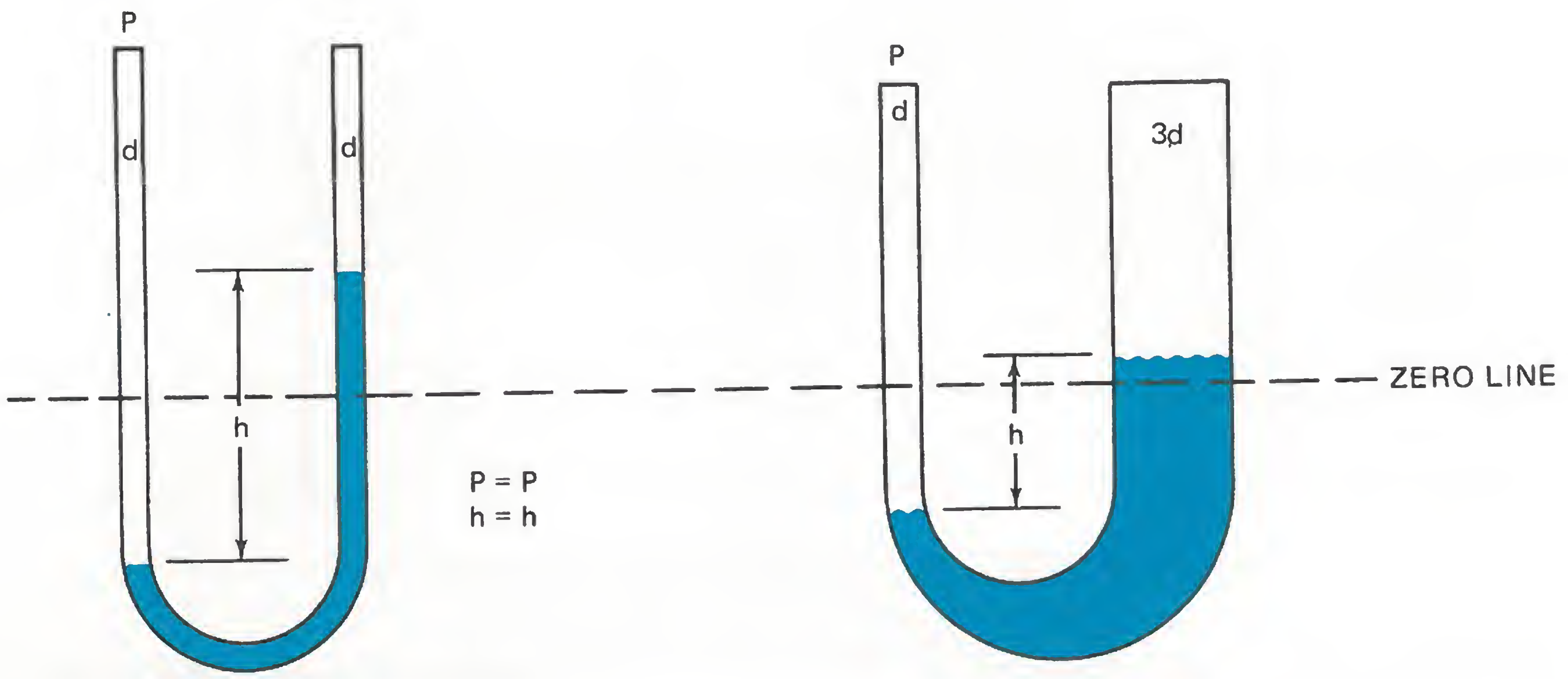
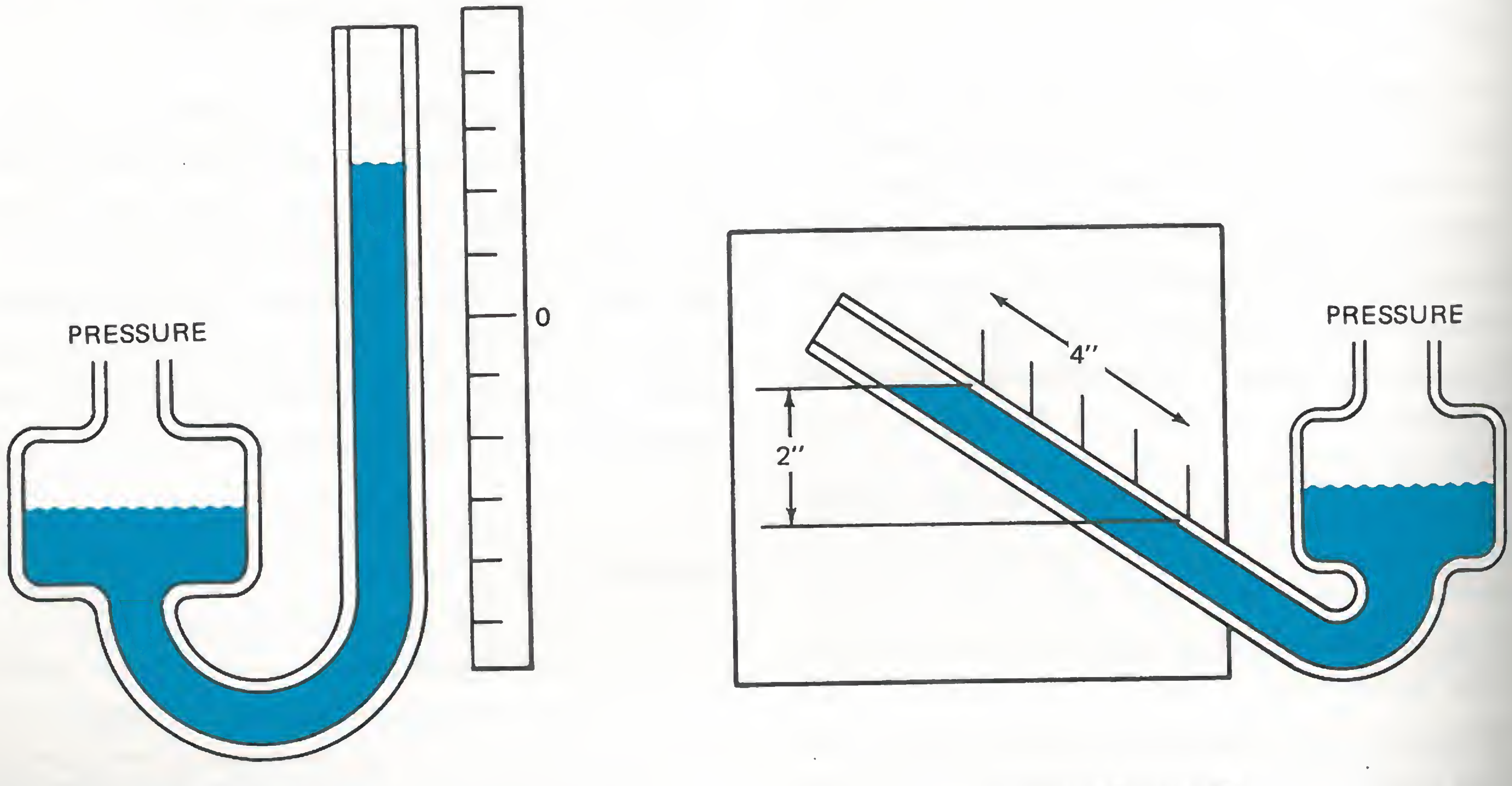


Fig. 7-4 Different Shapes of Manometers

pressure. However, the distance the liquid moves may not be the same for manometers with different cross-sectional areas. Figure 7-4 illustrates this point.

The hydrostatic balance provides that, regardless of any difference in the size or shape of the tubes, the difference between the column heights remains equal to represent a true measurement of the unknown pressure. This is due to the fact that the constant pressure which is applied to the left side displaces the same volume of liquid which moves up in the right side, regardless of the shape or size.

The U-tube manometer is not the only manometer used in measuring pressures. The well-type manometer shown in figure 7-5a and the draft gage shown in 7-5b can also be used, especially for low pressure ranges.



(A) WELL-TYPE *(B) DRAFT GAGE*

Fig. 7-5 Other Forms of Manometers

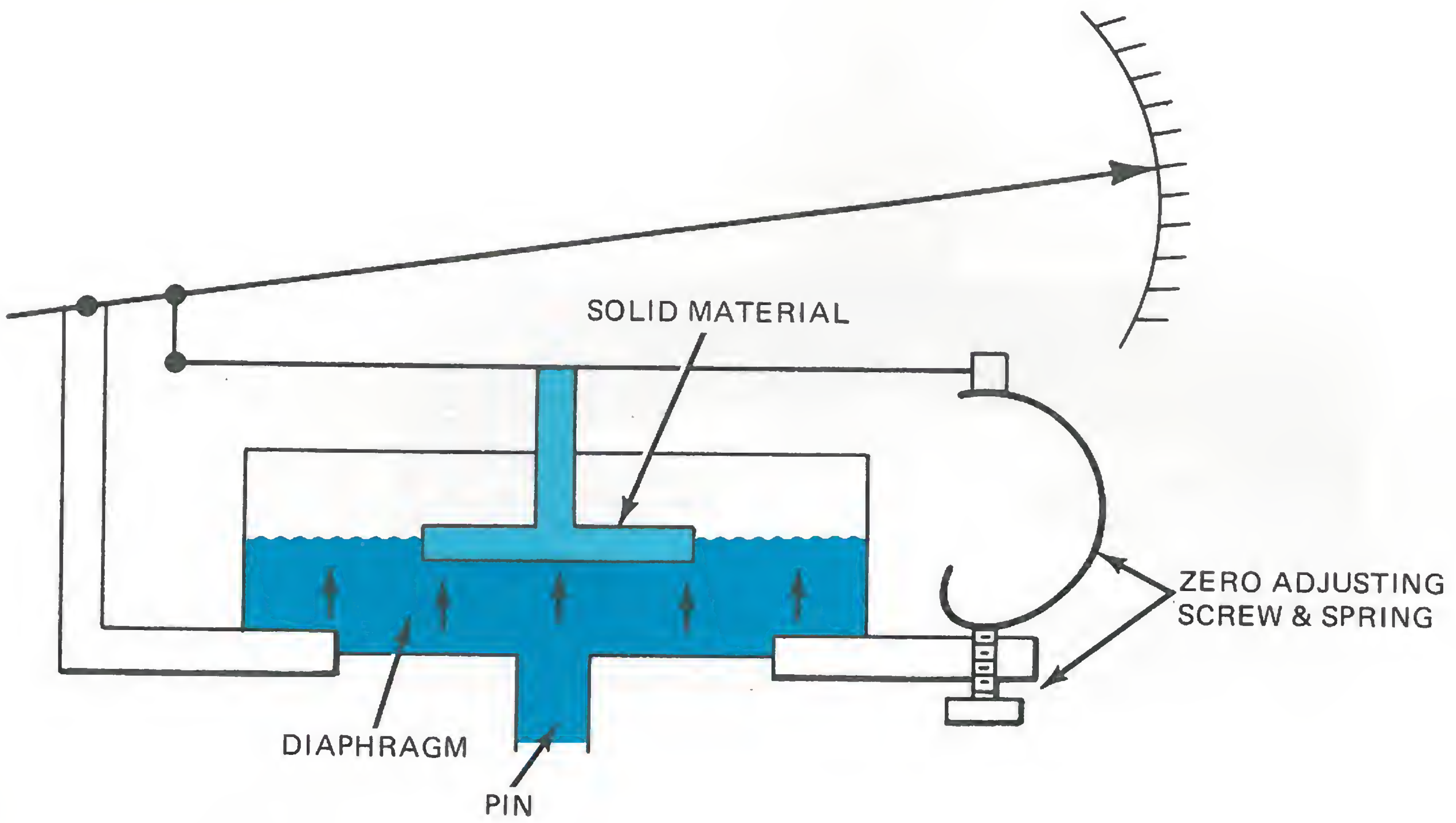


Fig. 7-6 Diaphragm Pressure Gage

A diaphragm is the element used in some devices to measure absolute and gage pressure. A diaphragm made of such materials as leather, teflon, and neoprene is best suited for low pressure ranges.

At the center of the diaphragm is a thin metallic disc or other rigid material. The diaphragms may not be circular, as some manufacturers use an elongated shape in their instruments. The diaphragm pressure gage is accurate from a range of 0 - 0.5 in. of water up to a range of 0 - 10 in. of water. Diaphragms are used for indicating, recording, and in controlling draft gages. Figure 7-6 shows one type of diaphragm used in industry to measure both pressure and vacuum.

A diaphragm can also be made of a stiff metallic material. One such diaphragm consists of a hardened and tempered diaphragm about 3 in. in diameter held by flanges as shown in figure 7-7. When pressure is applied to the under side, vertical movement is trans-

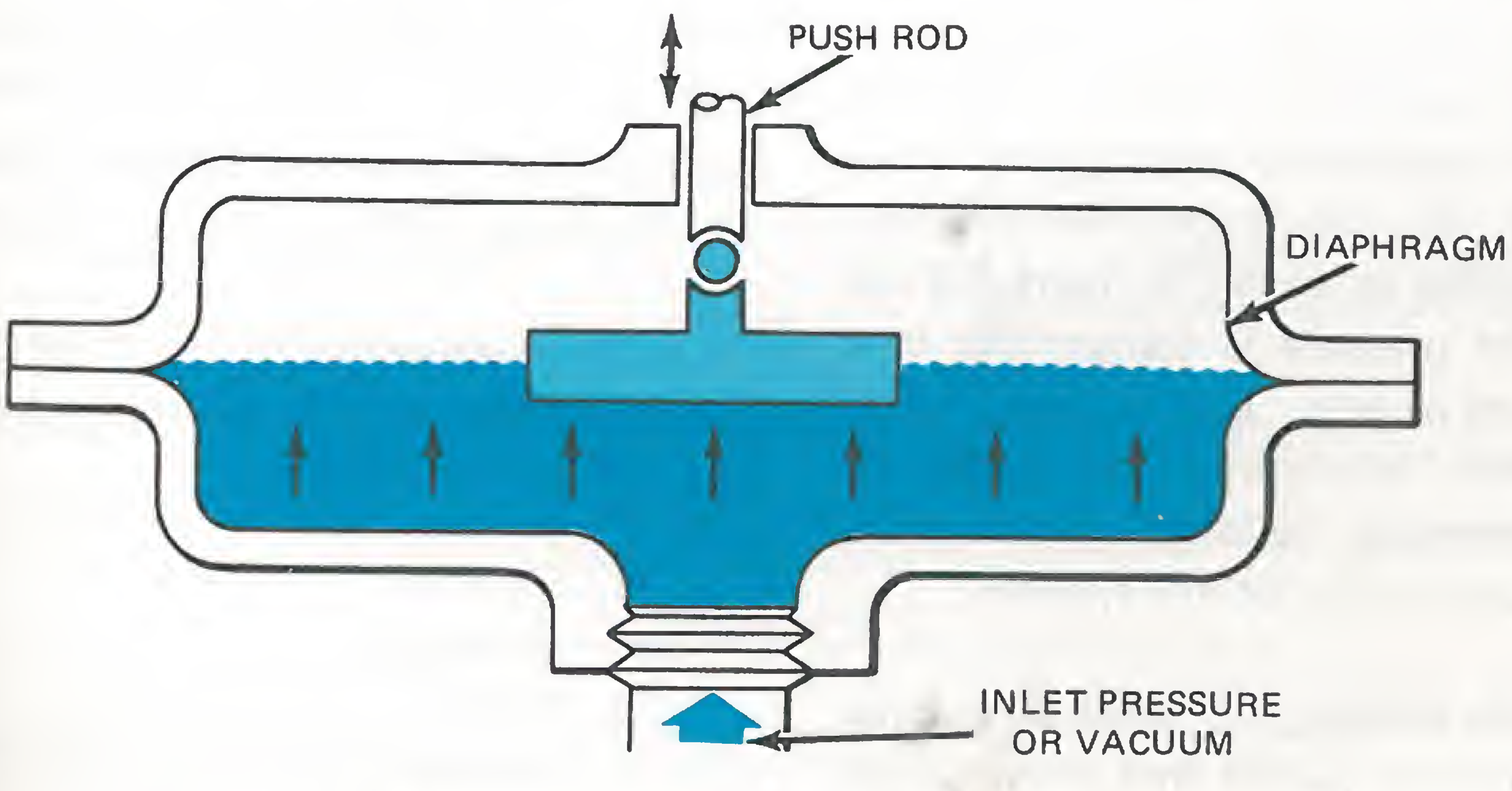


Fig. 7-7 Diaphragm Gage with Steel Diaphragm

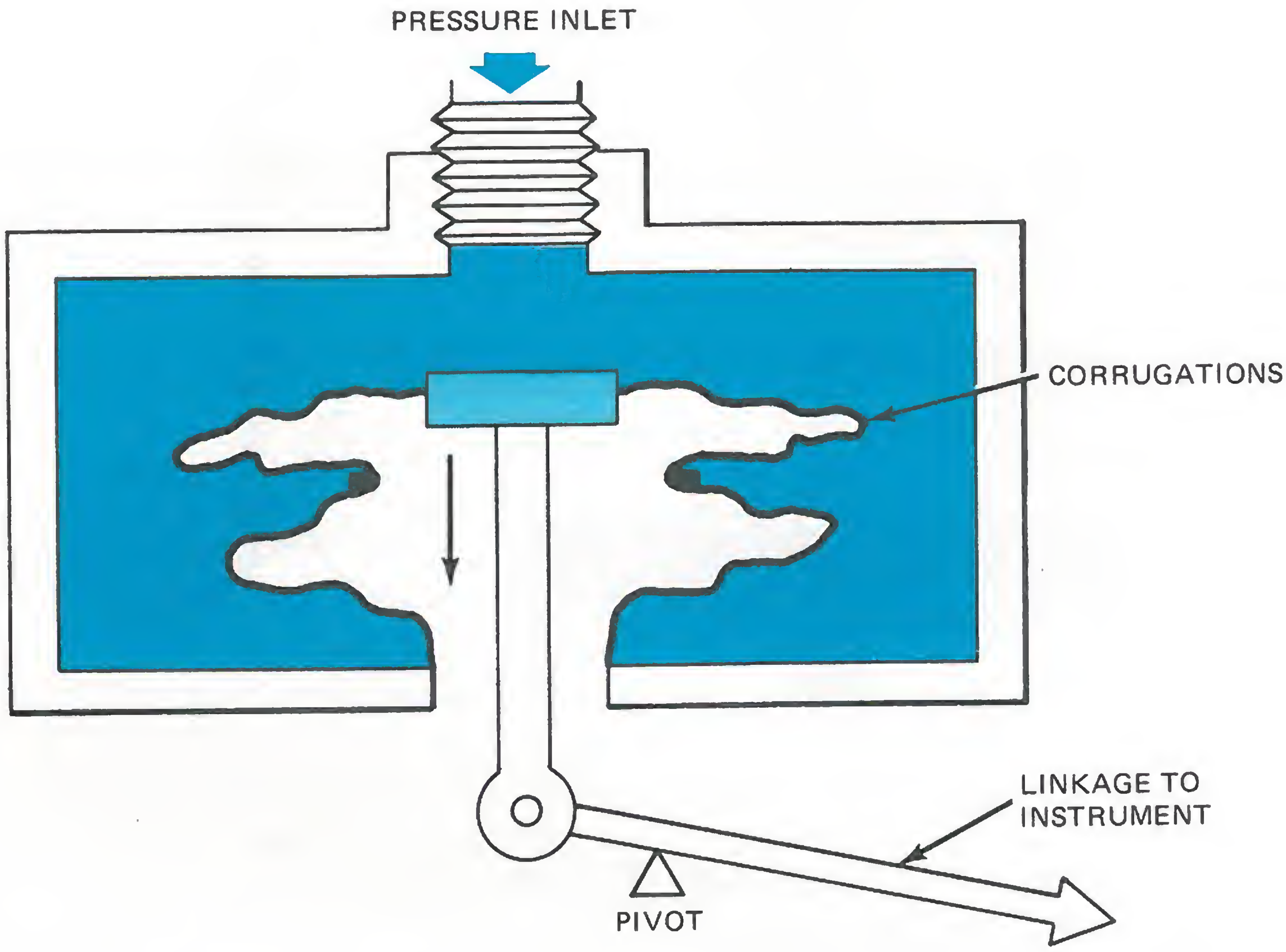


Fig. 7-8 Low Pressure Bellows

mitted to the ball-socket joint. The push rod can be connected to a pointer through linkages and lever systems to give a high magnification of movement across an appropriate scale.

Sometimes, two diaphragms are fastened together making a pressure capsule. Such capsules are used either singly or in stacks if the pressure to be measured is relatively high. The usefulness of corrugated diaphragms is increased when the diaphragms are stacked. Pressure is applied as shown in figure 7-8 and the differential pressure is transmitted to a pointer or control arm. Besides being called a capsule, this arrangement is sometimes called a low-pressure bellows. It is used a great deal in pneumatic control systems.

A metallic bellows is a series of circular parts so formed or joined that they can be expanded axially by pressures but not appreciably in any other direction. The material used is fairly thin and may have a large effective area. They can withstand far larger forces than are needed to strain them through a desirable distance. However, large deflections cut down on the cyclic life of a bellows.

By increasing the number of convolutions in the bellows, the axial movement or stroke can be increased. Small pressures can be measured by large diameter bellows which will increase the force for a given pressure.

There are many factors to be considered when determining the material used in a bellows. Some of these are:

1. *Strength.*
2. *Hysteresis.*
3. *Fatigue.*
4. *Corrosion resistance of the material.*
5. *Ease of fabrication.*

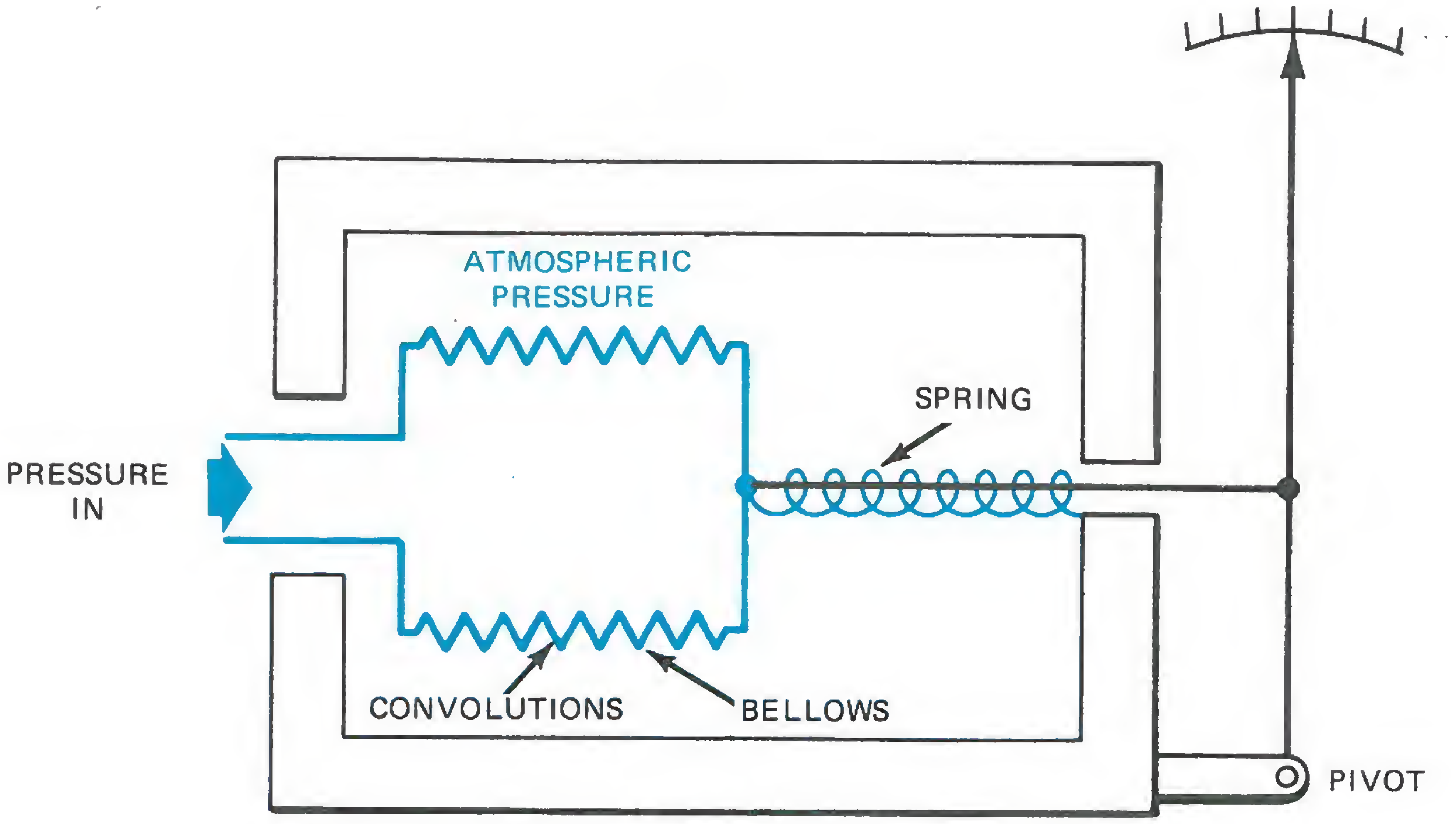


Fig. 7-9 Bellows-Type Pressure Gage

By proper choice of materials, convolutions, and calibrating spring, pressures from fractional parts of 1 psi up to 75 psi may be measured. The bellows assembly shown in figure 7-9 has atmospheric pressure acting on the outside of the bellows so it responds only to pressures different from atmospheric. In other words, the bellows is really a differential pressure instrument.

If a bellows-type gage is used to measure absolute pressure, the bellows may be enclosed in an airtight housing from which practically all air has been removed. Under these conditions, the bellows respond only to the one pressure and will indicate absolute pressure. Figure 7-10 shows an absolute pressure gage.

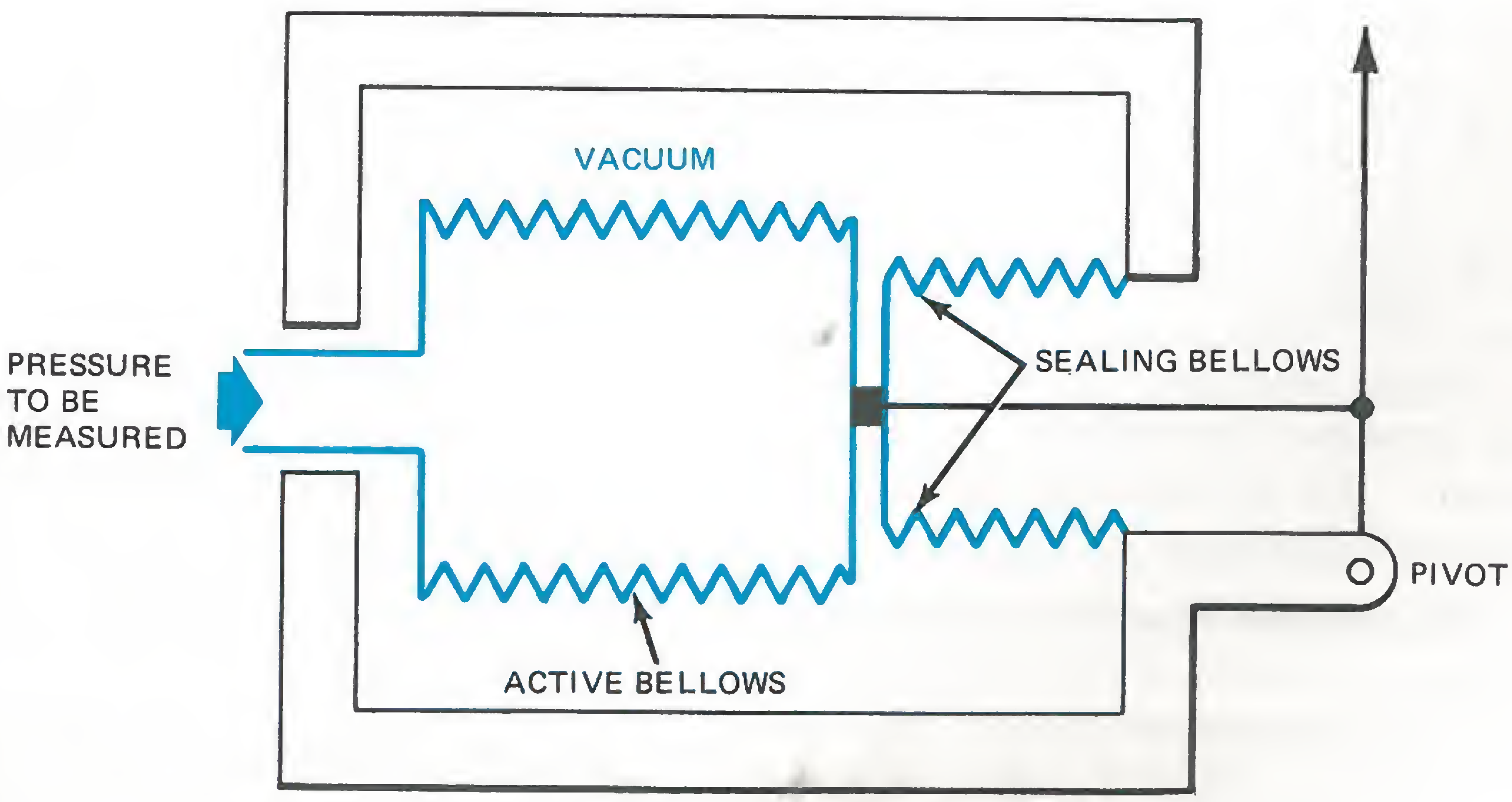


Fig. 7-10 Absolute-Pressure Gage

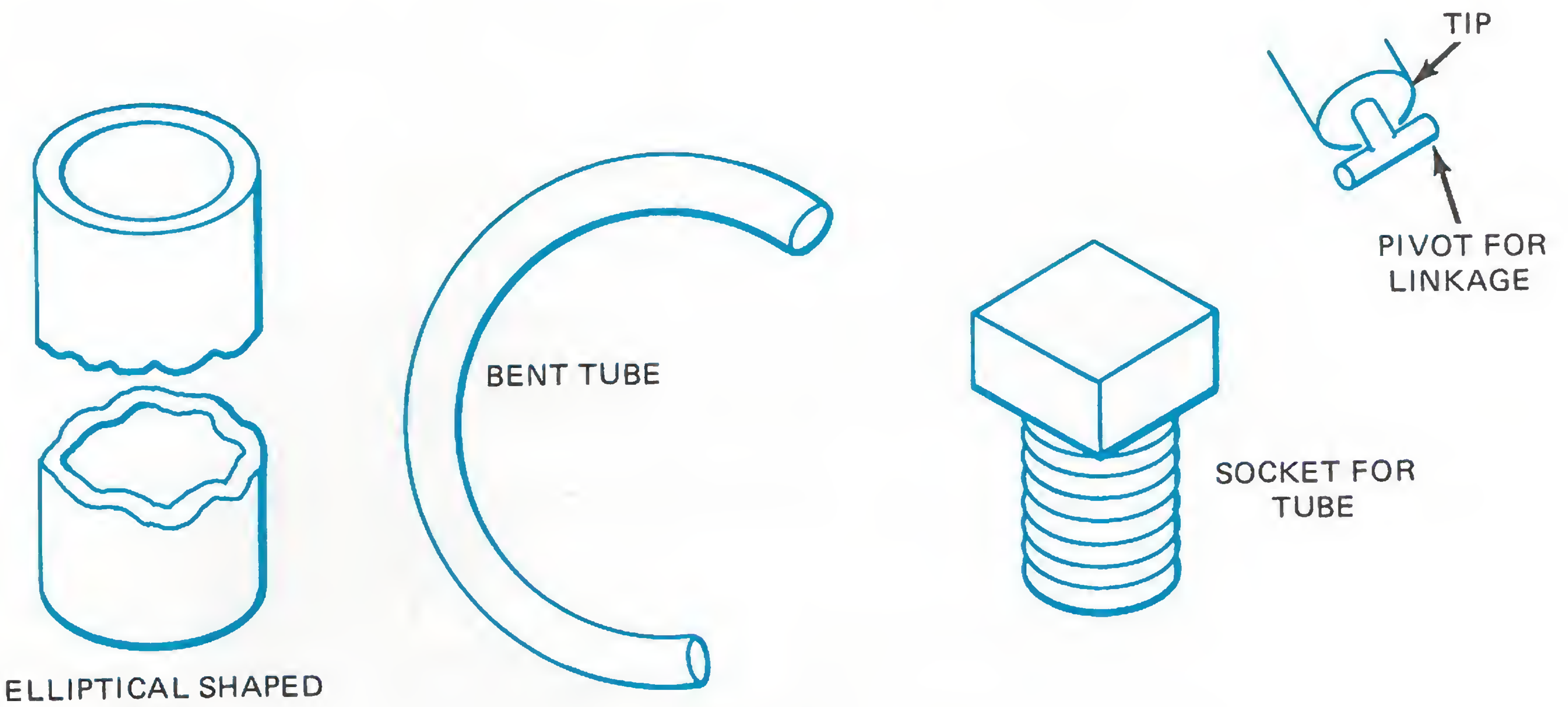


Fig. 7-11 Component Parts of a Bourdon Tube Gage

The increases in load and deflection changes are linear up to the elastic limit for the bellows material. However, this is true only when used under compression. For this reason it is necessary to arrange that the travel of the bellows be made on the compression side. The flexibility of the bellows is found to vary with the following physical characteristics:

1. *Directly* with the number of convolutions.
2. *Directly* as the square of the outside diameter of the bellows.
3. *Inversely* as the modulus of elasticity of the material.
4. *Inversely* as the cube of the wall thickness.

If thick walls are required to withstand higher pressures, the flexibility will be greatly reduced. This can be overcome by using a double-walled bellows.

The effective area of a bellows can be found by

$$\boxed{A = \pi \frac{R_o + R_1}{2}} \qquad (7.2)$$

where

A = effective area of bellows
R_o = outside radius of bellows
R_1 = inside radius of bellows

By knowing the effective area of the bellows and the total pressure, the total force that is exerted on the bellows can be calculated.

Another type of pressure measuring device makes use of the Bourdon tube. This type of gage is used for measuring pressure or vacuum and is one of the oldest instruments found in industry. Its effectiveness and reliability are extremely high. The component parts and mechanisms of a typical Bourdon tube gage are shown in figure 7-11.

The Bourdon tube behavior was observed in 1891 by Eugene Bourdon. He found that a round tube which had been flattened and bent into a circular arc would tend to return to its original shape when a pressure was applied inside it. The Bourdon tube gage is a length of thin-walled metal tubing which has been flattened and then rolled into a C shape, with an arc span of about 270°. The tube is sup-

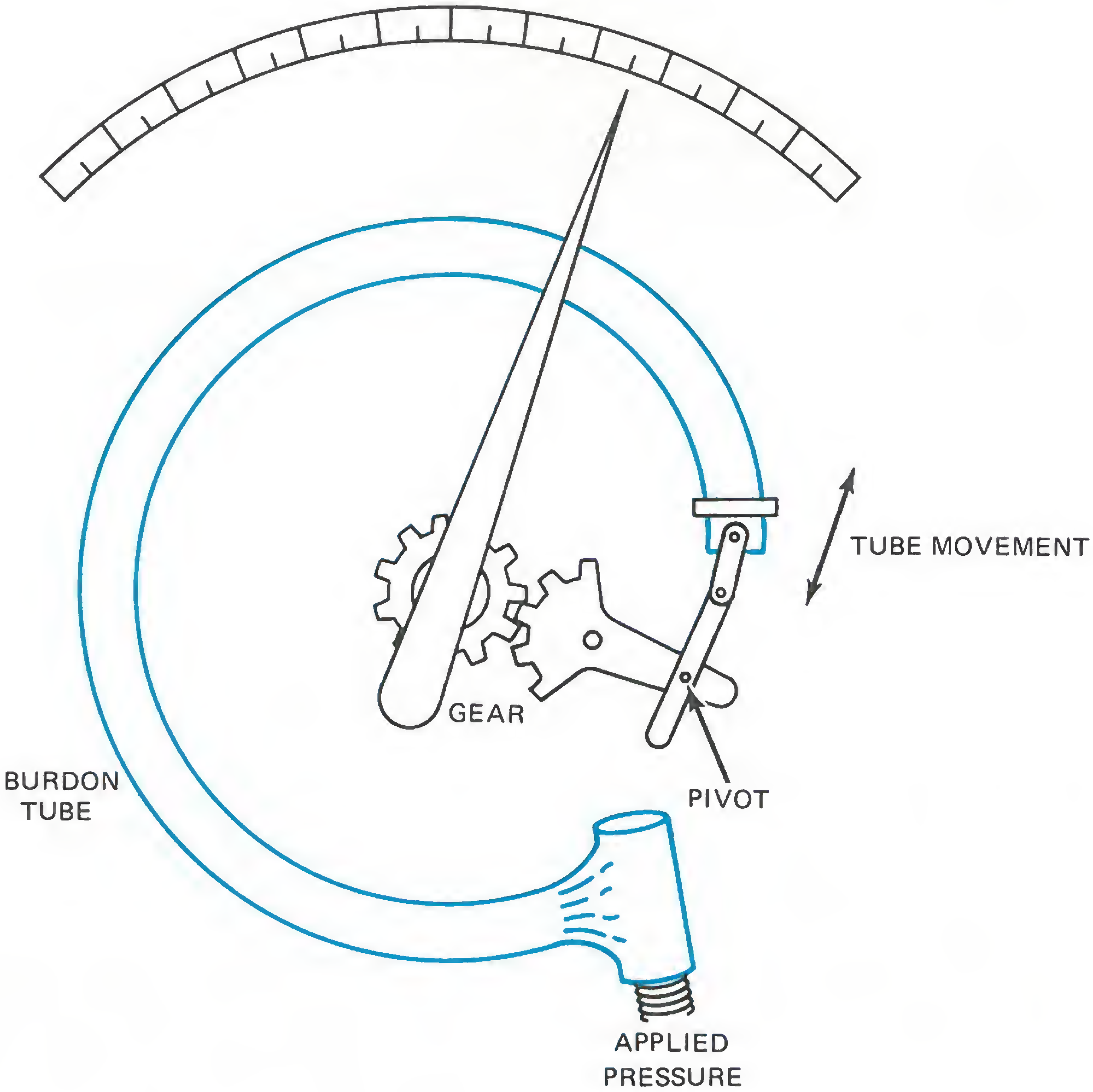


Fig. 7-12 Typical Bourdon-Tube Gage

ported in a socket which contains the pressure inlet. The free end of the tube is sealed and it, along with the socket, is welded, brazed, or soldered together according to the applied-pressure range.

The deflection of the tip depends upon the radius of the band, the total tube length, the wall thickness of the tube, the major and minor axes of the cross-section, and Young's Modulus of elasticity of the material. Under pressure, the elliptical or flattened section tends to change its shape to a circular form. As the stresses are set up, the tube begins to straighten out. A typical Bourdon tube gage is shown in figure 7-12.

The movement of the free end is transmitted to a pointer by way of a lever arm and gear. No external spring is used to alter or control the movement of the free end and virtually no external force is available to actuate the indicating mechanism. The pointer and the gear train are made to have a minimum of friction.

The Bourdon tube can also be bent into a spiral or helical form. In the spiral form the free end of the tube is wound around several times with the socket-pressure connection at the center. Figure 7-13 shows such a device.

The amount of movement varies directly

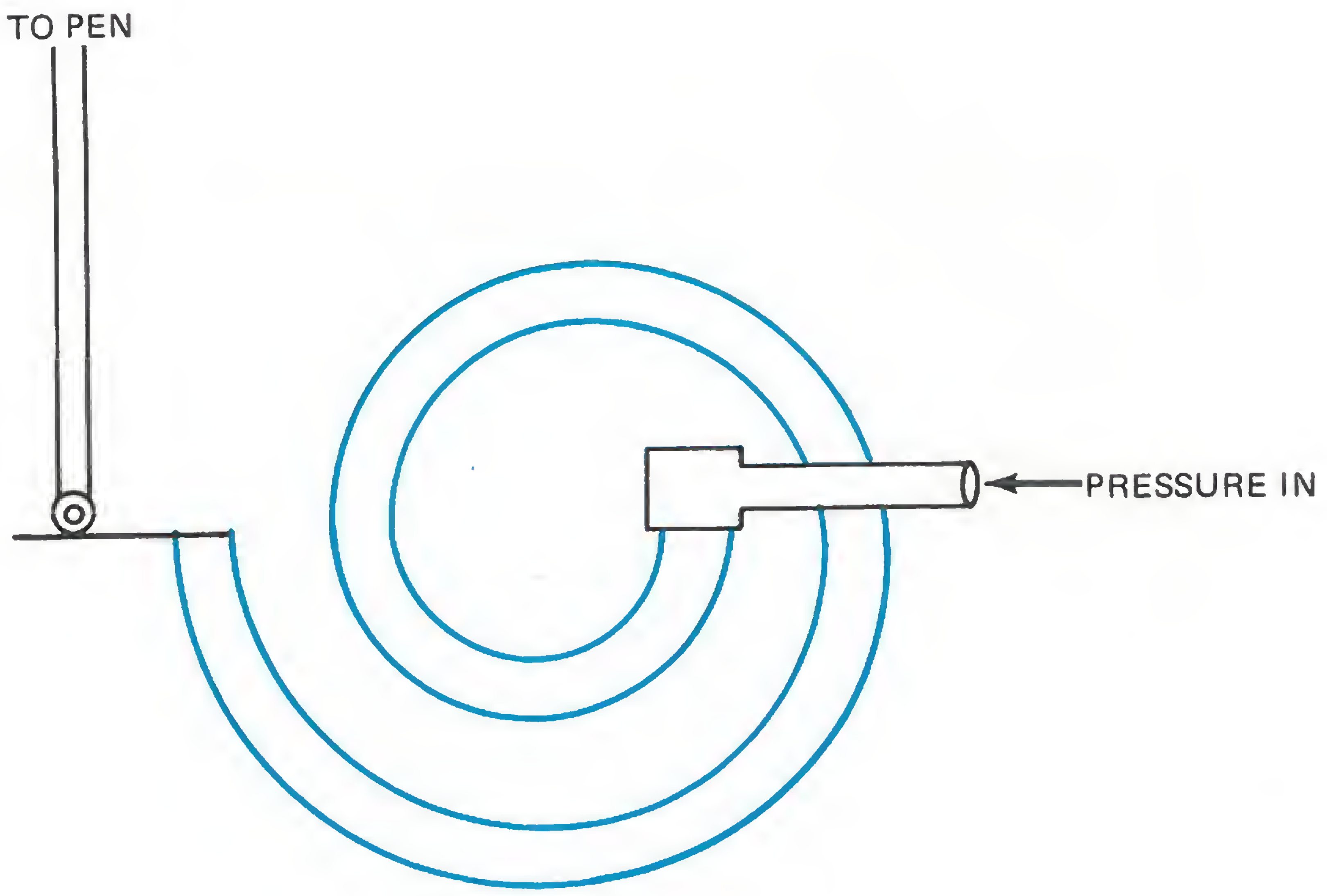


Fig. 7-13 Spiral Bourdon Tube

with the angle subtended by the total arc. By increasing the number of turns, a greater movement of the tip is obtained. This arrangement along with the helix tube is used when it is desirable to get more movement than can be obtained from a single turn such as was shown in figure 7-12.

The advantage of the helical type Bourdon tube is that the mean diameter of the turns can be kept fairly constant over a wide range of pressure. This means that a large instrument case is not necessary. A typical helical Bourdon tube is shown in figure 7-14.

The pressure range, number of operating cycles, ease in forming, and the pressure-exerting substance inside the tube will dictate the material to be used in the tube construction. Such materials as beryllium copper, phosphor bronze and steel are generally used. For low pressure ranges, phosphor bronze is usually preferred.

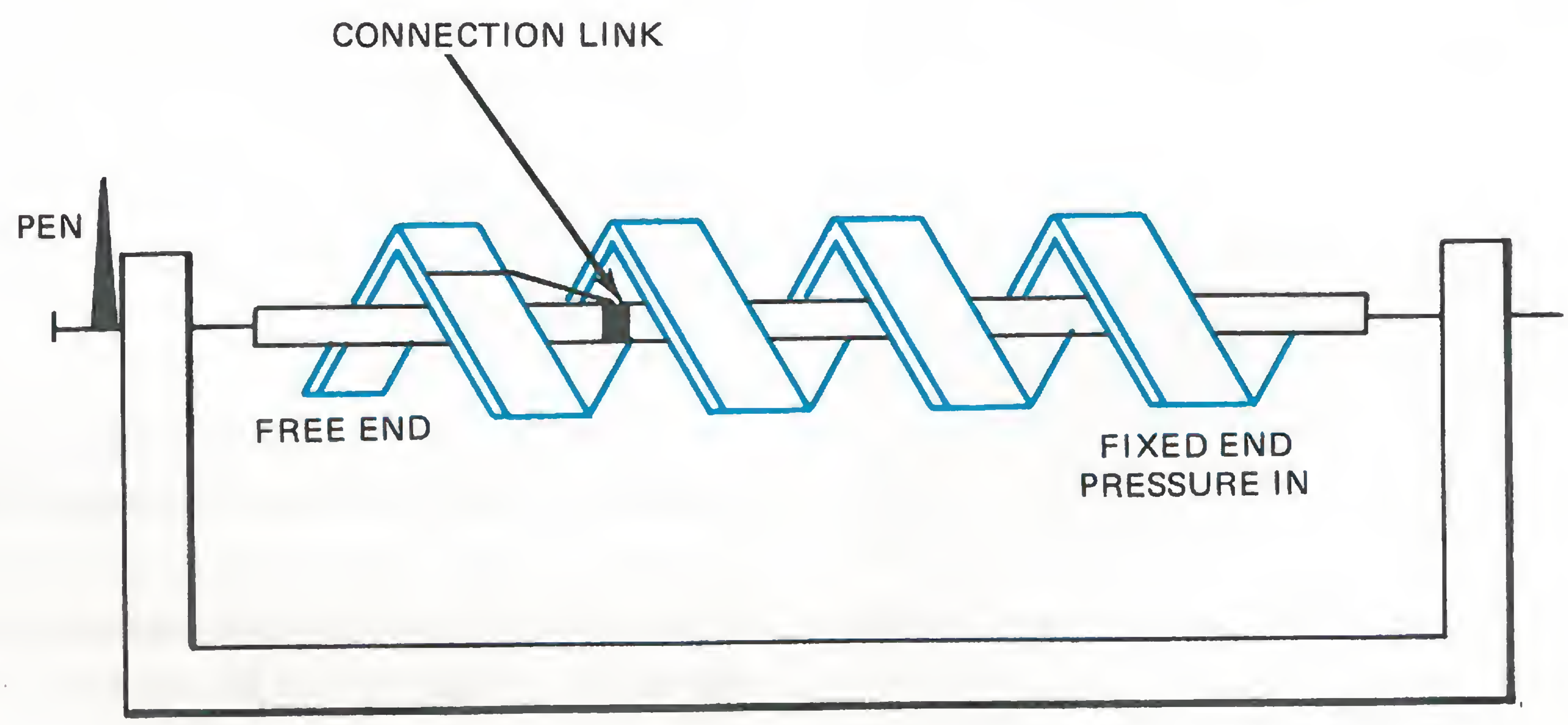


Fig. 7-14 Helical Bourdon Tube Gage

MATERIALS

2 Bellows assemblies mounted in cases 1-1/4 - 1-1/2 in. dia.
1 Breadboard
2 Pressure plates
1 Shaft ≅ 5 in. long
1 Lever arm 12 in. long
1 Pointer indicator
1 Spring 2 in. long
1 Slider block with 2 set screws
1 Solid block for pivot point
Additional angles and braces as needed
Nuts and bolts as needed
1 Air supply
1 Air regulator
1 Air pressure gage 0 - 30 psi
1 Vacuum pump
1 Vacuum gage 0 - 30 in. of mercury
Air hose and fittings as needed
1 Sheet of graph paper

PROCEDURE

1. Assemble the parts as shown in figure 7-15A and B.

2. The bellows should be mounted so that they are free to move in and out. They should be mounted about 5 inches apart on the same level. The pressure plates must be adjusted in and out to compress the bellows up to but no more than 1/2 of their travel. The pointer assembly should be free to rotate as the shaft moves. The pointer lever should be in a 1:10 ratio or greater so that the slight movement of the bellows will cause a large movement at the end of the pointer. Be sure that all parts are tight and there is only movement of the bellows and pointer lever when all parts are assembled. A spring placed in tension opposite the bellows where the air supply is connected will help with the play associated with the pointer assembly. It will also pull the pointer during the vacuum part of the experiment.

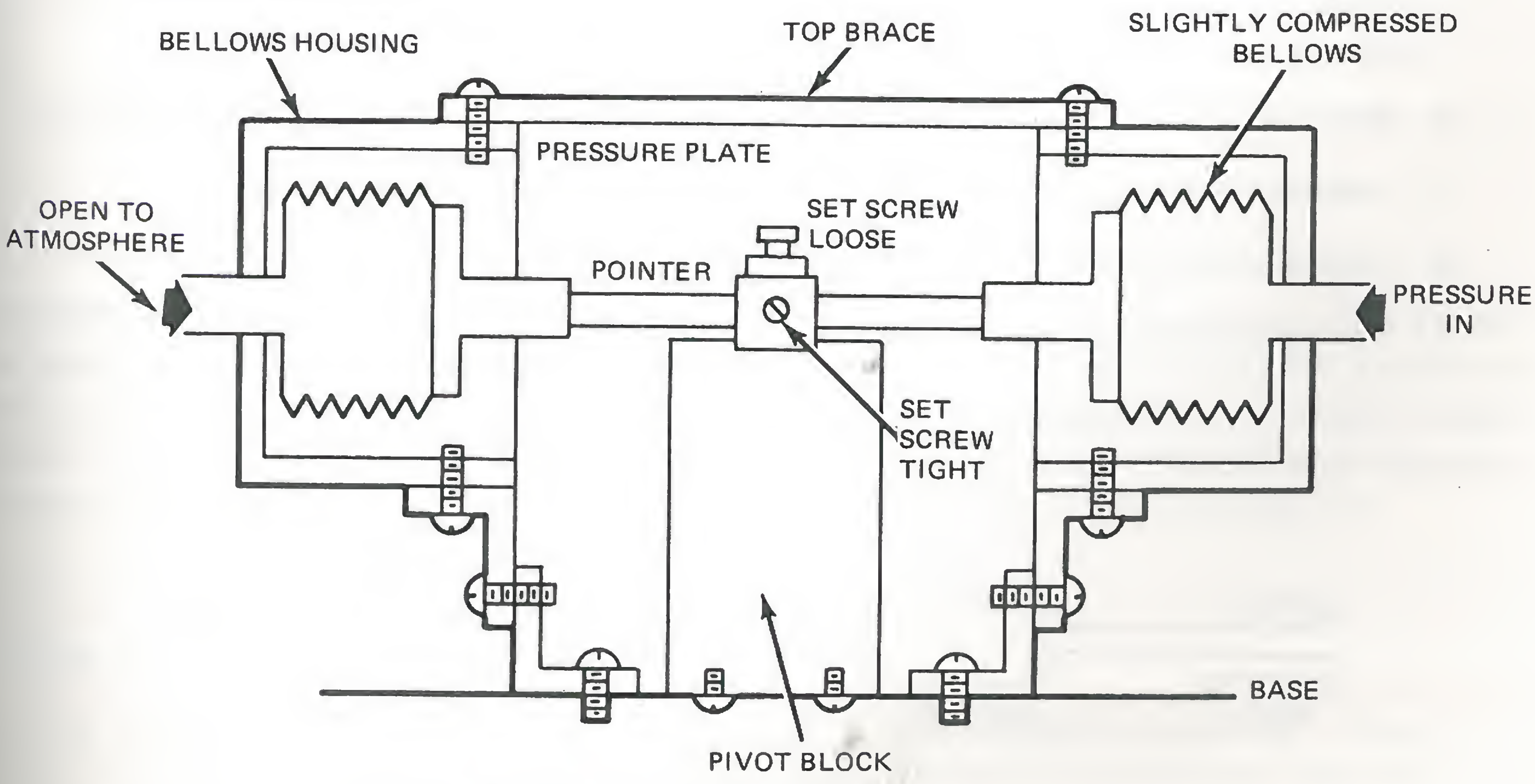


Fig. 7-15A Side View of Bellows Assembly

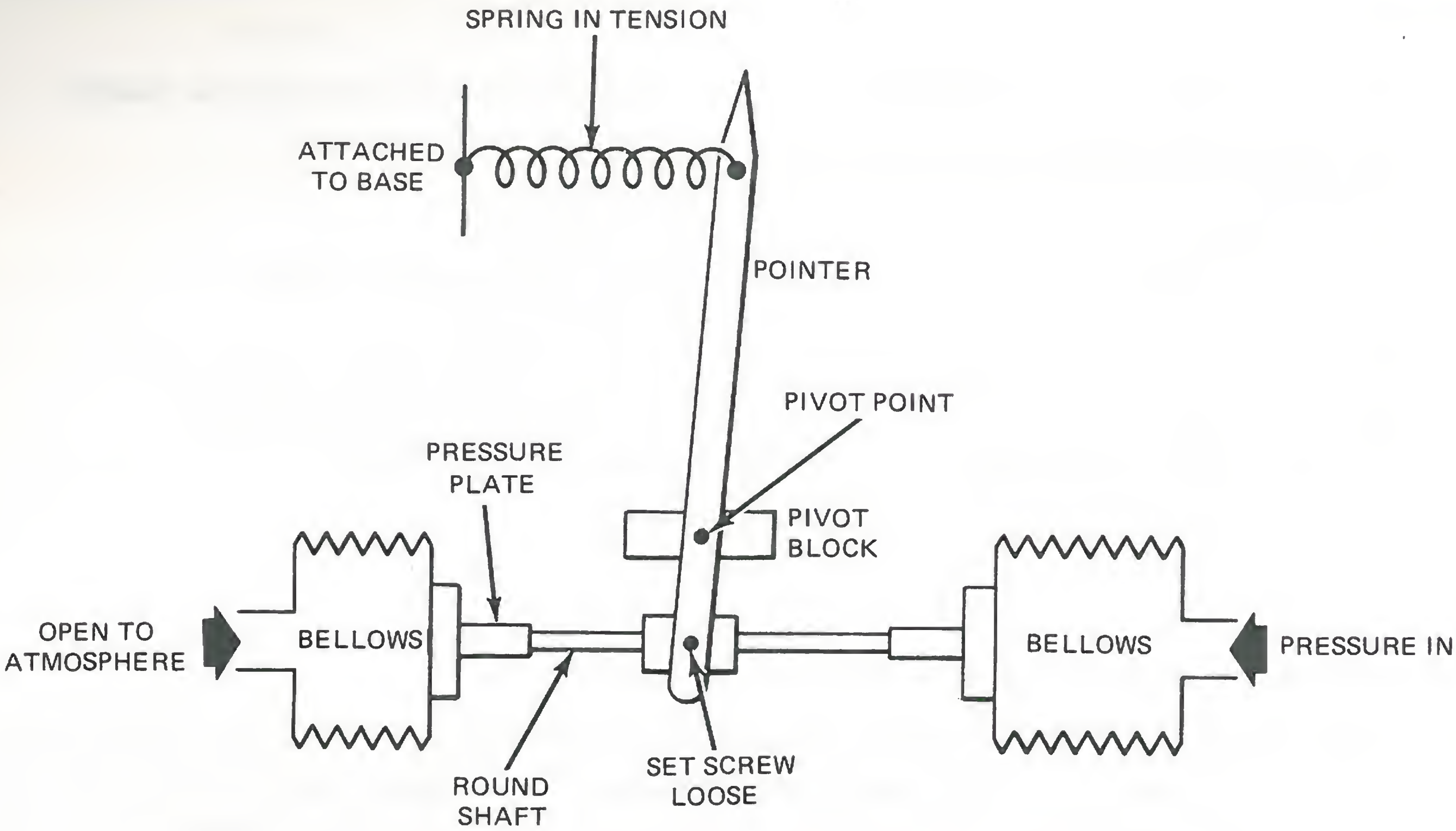


Fig. 7-15B Top View of Pointer Assembly

3. Attach the air supply to one side of the assembly as shown in figure 7-16.
4. Place a piece of graph paper on the base of the bellows assembly in such a position that the pointer will move over the top of it.
5. The zero gage pressure point can be adjusted one way or the other by loosening the set screw on the shaft between the pressure plates and moving the pointer assembly. Set the pointer position so that it corresponds to a major line on the graph paper.
6. With zero pressure indicated on the gage, mark the pointer position and label it zero.
7. Increase the pressure to 4 psi. Mark the position of the pointer on the paper.
8. Increase the pressure in 2-psi increments and mark and label each position of the pointer.
9. Continue increasing the pressure until no more movement is indicated by the pointer.

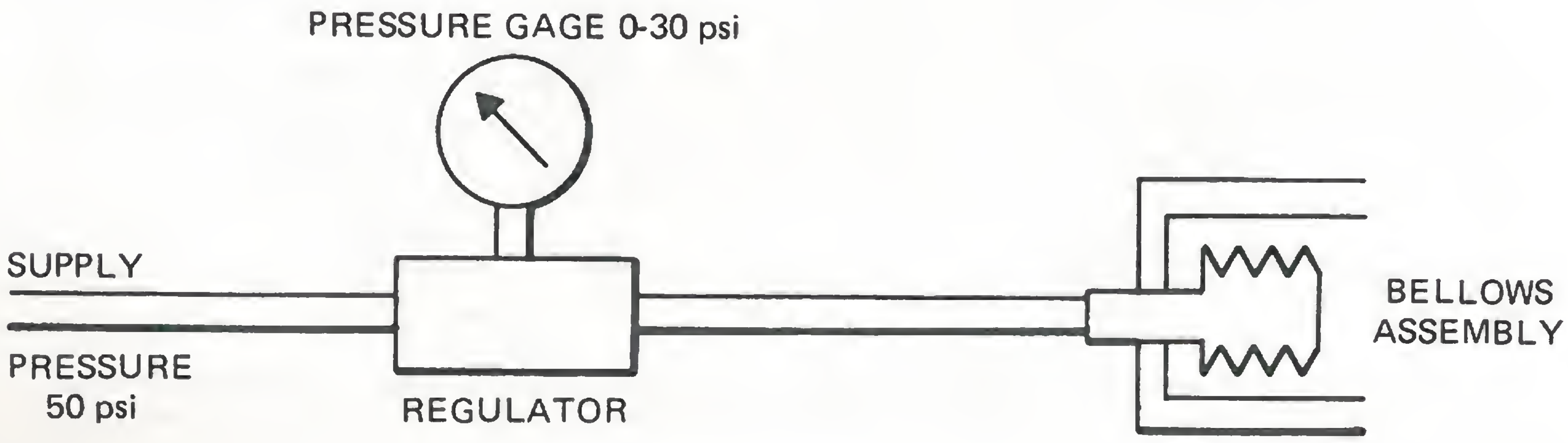


Fig. 7-16 Air Supply

10. Decrease the pressure in 2-psi increments and mark and label the points as the pressure is decreased to zero.

11. Disconnect the air supply and attach the vacuum pump as shown in figure 7-17 to the same bellows.

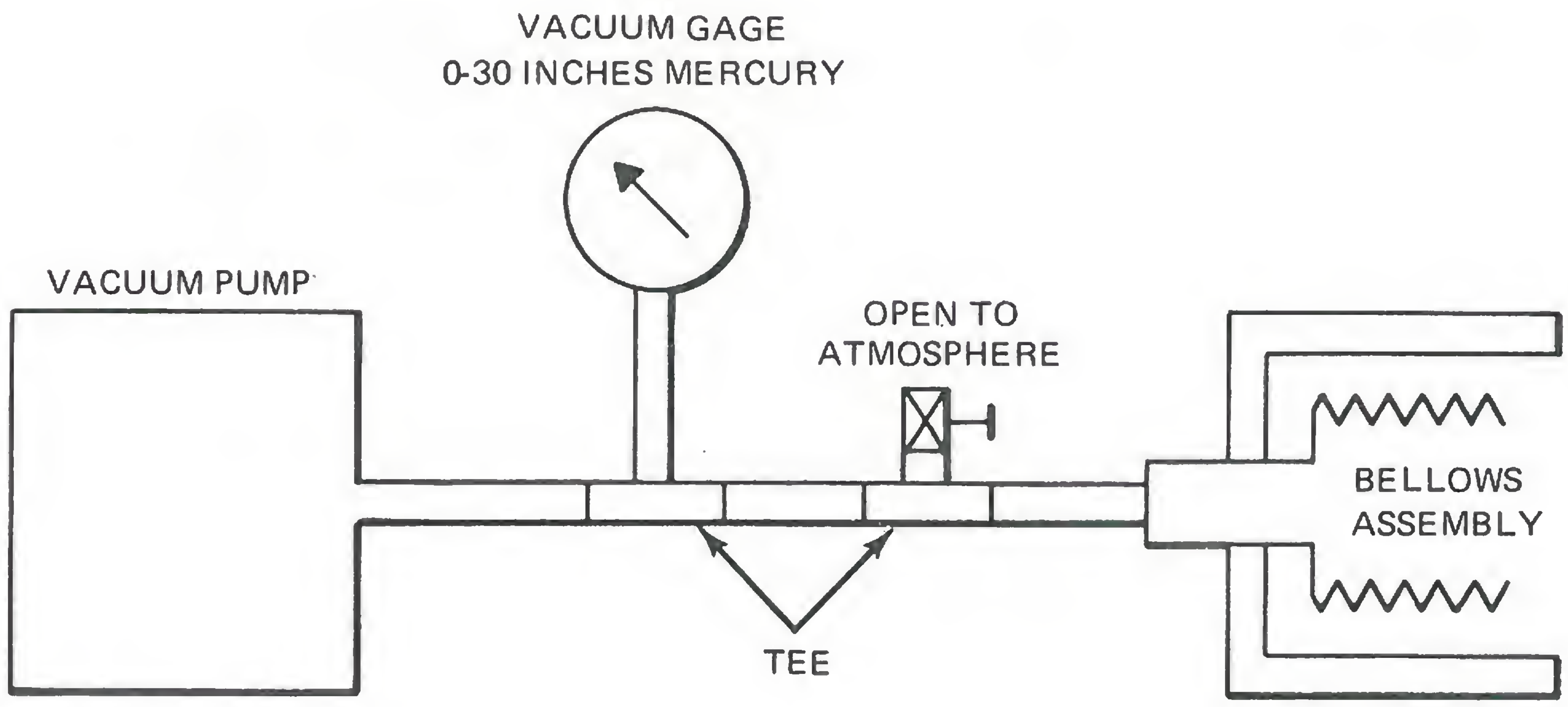


Fig. 7-17 Vacuum Assembly

12. Pull a vacuum on the bellows and mark the position of the pointer for each 5 inches of mercury. You may have to adjust the restrictor valve so that the vacuum is not applied too fast to record.

13. Increase the vacuum until the pointer no longer moves.

ANALYSIS GUIDE. Measure the distance traveled between each 2 psi recordings. Plot a graph of pressure versus distance traveled for the bellows used. Explain why the distance around the zero pressure range and the maximum pressure range are not as linear as in the middle ranges. How could this assembly be calibrated to be used to measure pressure? This particular assembly measures gage pressure. How could this assembly be changed to read absolute pressure?

PROBLEMS

1. A 200-lb man sits in a 4-legged chair so that 3/4 of his weight is supported. If each leg has a cross-sectional area of 1 sq. in., what pressure in atmospheres does each leg exert on the ground?

2. A lever with a mechanical advantage of five is attached to the pump piston of a hydraulic press. The area of the pump piston is 2 in.^{2} and that of the output piston is 40 in.^{2}. Find the force the output piston exerts when a force of 30 lbs is applied to the pump lever? Assume no losses.

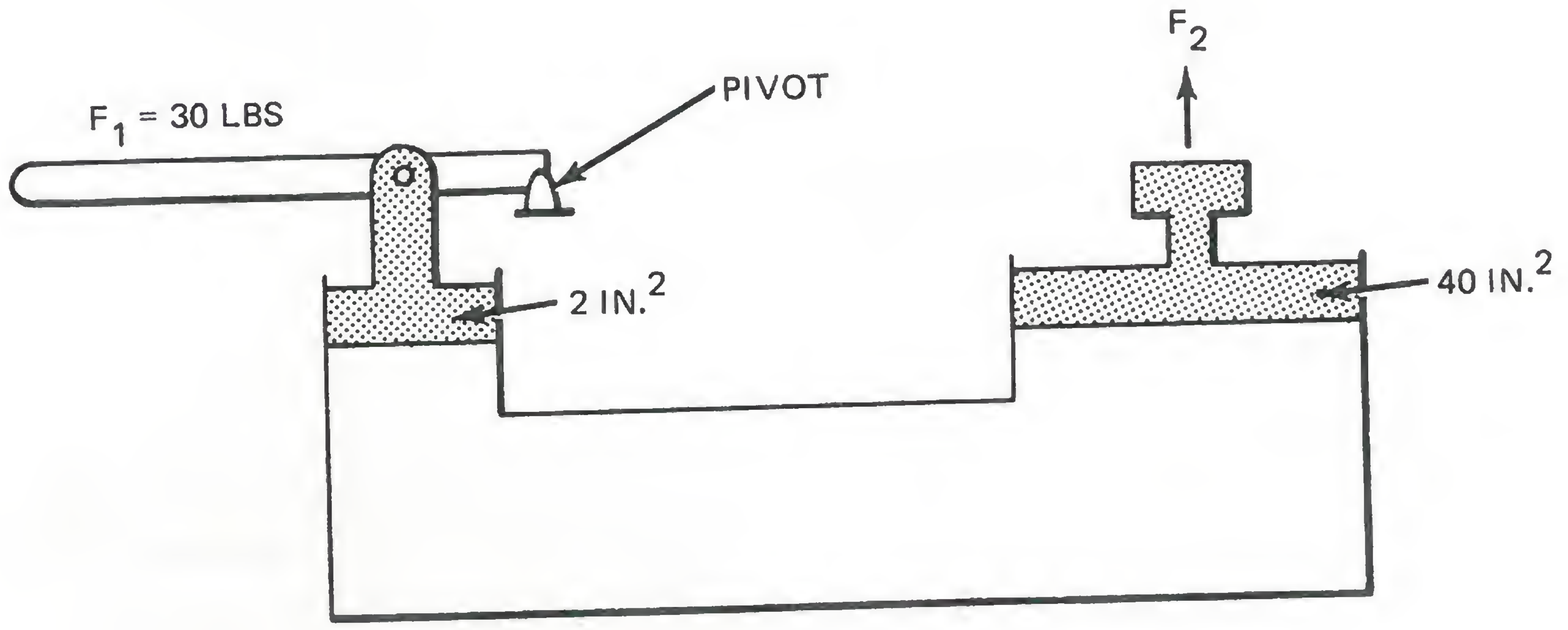


Fig. 7-18 Hydraulic Pump

experiment 8 PRESSURE TRANSDUCERS

INTRODUCTION. The space age has caused a necessity for sensitive and accurate measurements. A pressure transducer has certain input-output characteristics that satisfy these demands. In this experiment we will examine some of the characteristics of a pressure transducer.

DISCUSSION. The terms transducer, sensor, gage, and pickup, as applied to instrumentation, denote that the magnitude of some input is converted to some measurable output. Properly defined, *a transducer is a device which converts energy from one or more systems of energy to energy of another system.* The energy input and output may be in any form.

Pressure transducers are one of many types of transducers used in instrumentation. There are a number of different types of pressure transducers depending on the application involved. The characteristics of some of these transducers will be examined.

A barrel-type pressure transducer is shown in figure 8-1. It has a cylindrical tube with one closed end. The fluid under pressure is applied to the inside at the flange end. Neglecting end restraints, the tangential stress at the inside of the tube with radius r_1 is

$$\boxed{\sigma_i = P\,\frac{n^2 + 1}{n^2 - 1}} \tag{8.1}$$

and at the outside of the tube with radius r_o

$$\boxed{\sigma_o = \frac{2P}{n^2 - 1}} \tag{8.2}$$

where

σ_i = stress inside tube

σ_o = stress outside tube

P = pressure applied

n = ratio of the outer to inner ratio $\dfrac{r_o}{r_i}$

The tangential stress at the outside of the tube will be smaller than the stress at the inside of the tube.

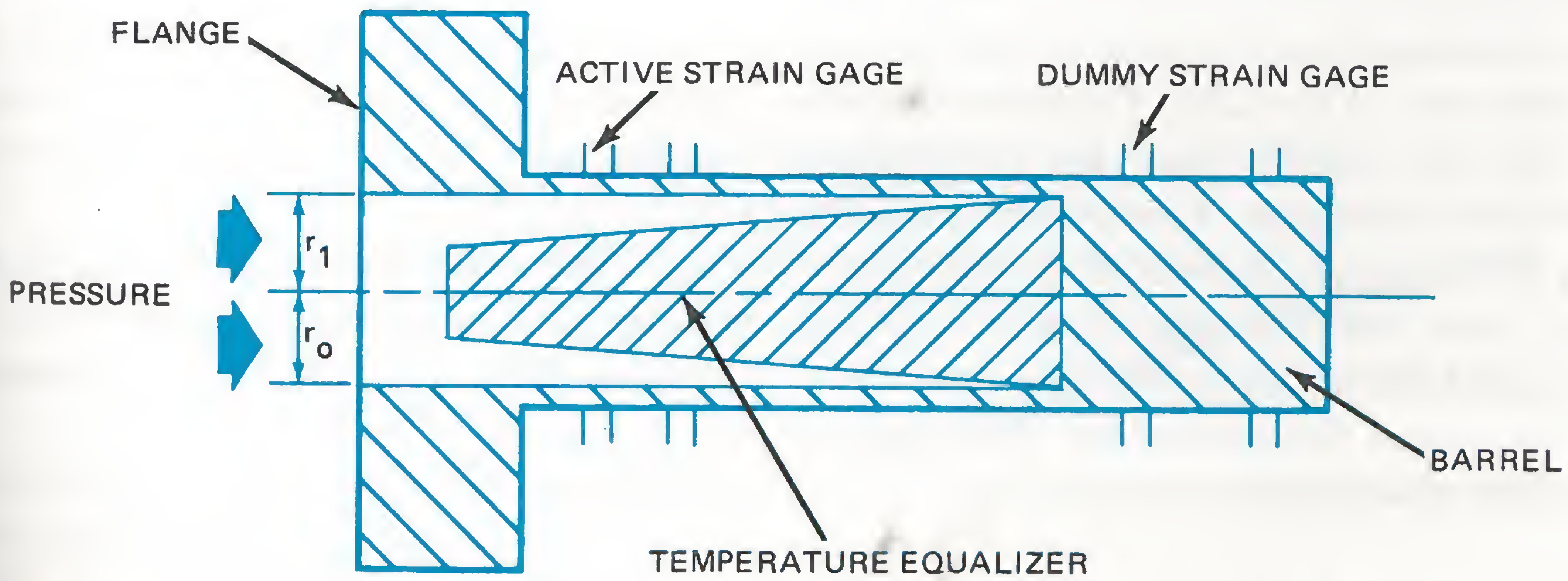


Fig. 8-1 Schematic of a Barrel-Type Pressure Transducer

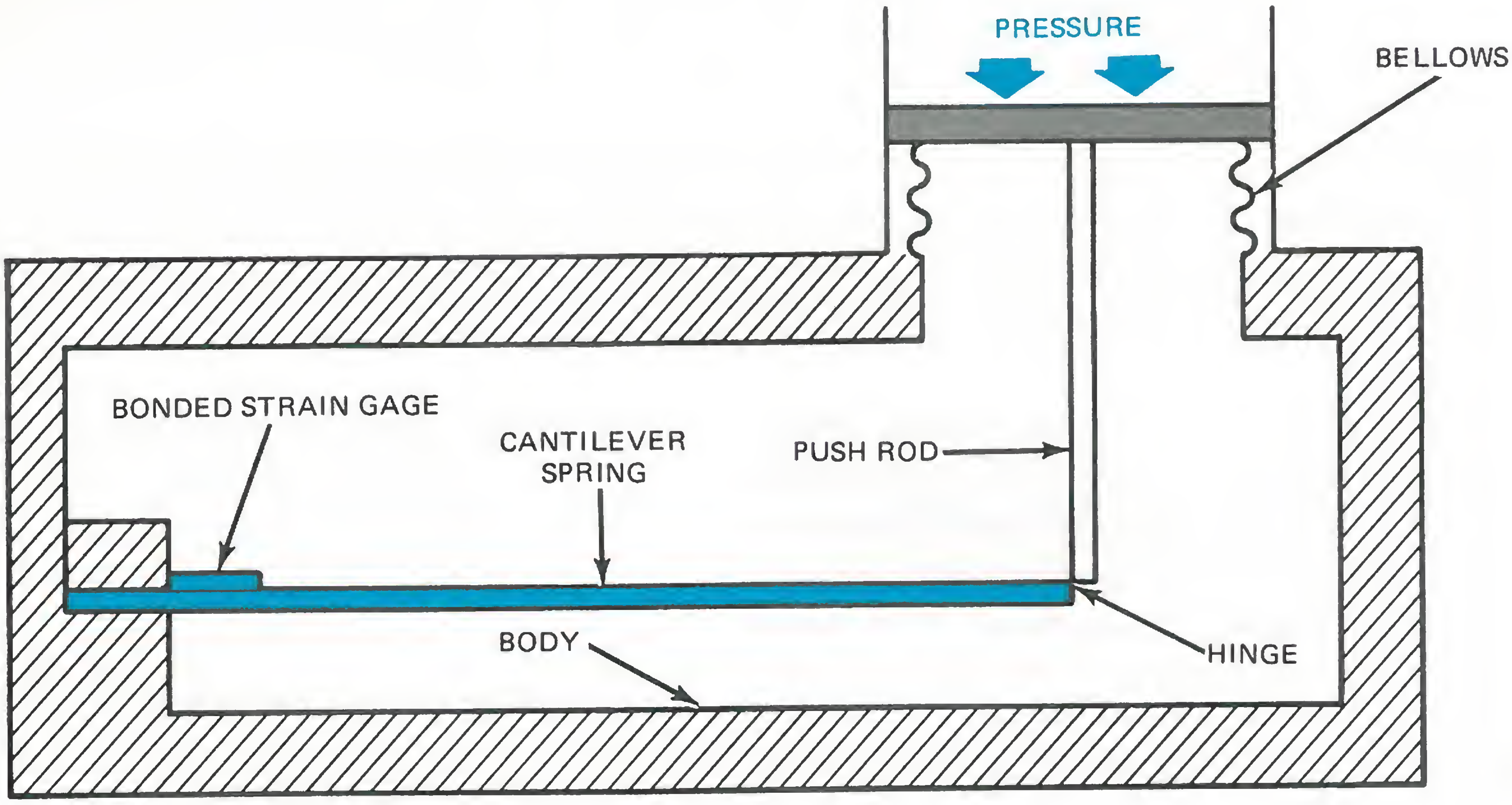


Fig. 8-2 Schematic of a Cantilever-Type Pressure Transducer

The strain obtained on the outer surface is inversely proportional to the wall thickness. The smallest wall thickness likely in practice is approximately 0.0075 inches. Larger tubes normally require thicker walls. Assuming a working strain of 10^{-3}, the lowest possible pressure range for steel tubes is approximately 1000 psi. Higher pressure levels can be obtained with different flange arrangements up to approximately 20,000 psi.

Two helical windings of strain gage wire are secured around the barrel part of the tube, representing the two active arms of the bridge. Two compensating windings are bonded to the solid part of the tube. The dummy windings will very nearly equal the temperature of the active windings. Temperature gradients along the tube can be reduced by means of a copper cone inside the barrel which is fixed to the solid end of the cavity. The cone transfers heat from the pressurized fluid into its tail which equalizes the temperature.

Transducers of this type are used for both static and dynamic measurements. The biggest disadvantage of this transducer is its small overload margin: that is, to get maximum output, the tube must be stressed close to its limit. One must be careful to avoid stressing the tube too far to avoid ruining the device.

The cantilever-type of transducer consists essentially of a flexible pressure-sensitive element which, by way of a push rod, transmits its force to a spring that has strain gages attached. Figure 8-2 illustrates this type of pressure transducer with a cantilever actuator.

There are a number of physical arrangements used in this transducer to actuate the strain gage. Figure 8-3 shows a few of these.

The cantilever stiffness should be relatively high as compared to the pressure-sensing elements because of the hysteresis inherent in the pressure-sensing element. The cantilever strain is directly proportional to the force applied by the physical pressure mechanism. For example, suppose the area of the piston in figure 8-2 is one inch squared

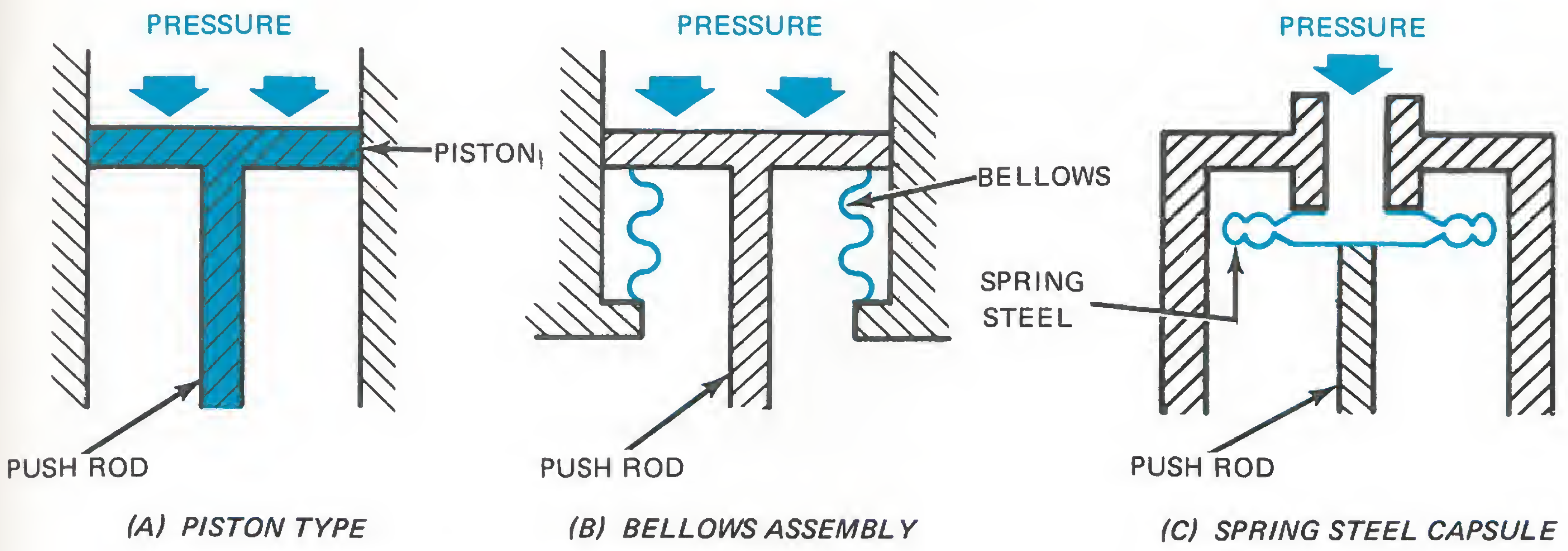


Fig. 8-3 Pressure Transducers with Different Types of Actuators

with a pressure of 500 psi. Applying Pascal's principle one would have

$$F = P \times A \tag{8.3}$$

The diaphragm-type pressure transducer is perhaps one of the more simple types of transducer. The strain gages may be bonded to one or both sides of the diaphragm. Unfortunately, this type of sensor device has only limited use because of the nonlinearity of the strain/pressure relationships. The reason for this is that greater expansion occurs at or near the center of the diaphragm. Figure 8-4 illustrates this point. The *radial stress* is greater near the edges and for small deflections or loads is given by

$$\sigma = \frac{3}{4} P \left(\frac{r}{t}\right)^2 \tag{8.4}$$

where

σ = stress

P = pressure difference between the two sides of the diaphragm

r = diaphragm radius

t = diaphragm thickness

At higher loads the stress becomes nonlinear

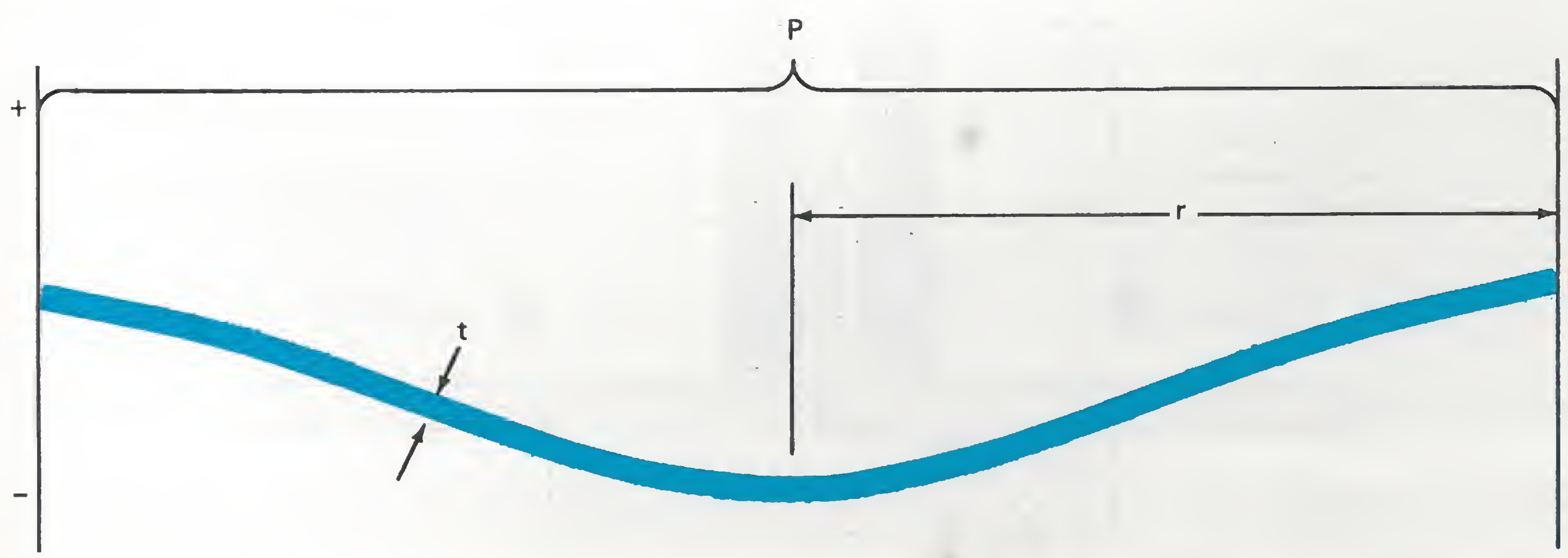


Fig. 8-4 Stress Distribution in a Clamped Circular Diaphragm

Ratio r/t		10	100	1000
Pressure (Max.) (psi)	P	10^4	1	10^{-4}
Strain	Σ	2.6×10^{-2}	2.6×10^{-4}	2.6×10^{-6}
Stress (psi)	σ	80×10^4	80×10^2	80

Fig. 8-5 Pressure, Strain, and Stress of Circular Steel Diaphragms for Linear Pressure/Strain Relationships

with the load and can be expressed as

$$\sigma = B\frac{Pr^2}{t^2} \qquad (8.5)$$

where B is a function of the load factor Pr^4/Et^4. Figure 8-5 shows the maximum pressure ranges of circular steel diaphragms which are acceptable in order to avoid non-linearity.

It may be observed that for a very thick diaphragm, r/t ratio of 10, the calibration is linear up to pressures of 10,000 psi but the strain is higher than is permissible for a resistance strain gage. The advantages of this type of pressure transducer are high natural frequency and low sensitivity to acceleration.

The dielectric constants of gases, liquids, and solids vary with pressure. These constants can be measured with the use of a capacitive transducer. Figure 8-6 shows one type of capacitive transducer that is sometimes used in wind tunnel measurements.

This transducer has as its actuator or sensor two electrodes and a diaphragm. The deflection of the diaphragm is detected by the variation of capacitance between it and the insulated electrodes. The diaphragm and electrodes are connected to three individual cables by way of a connector block. The transducer operates on a low differential pressure of ±4 lb/sq. in.

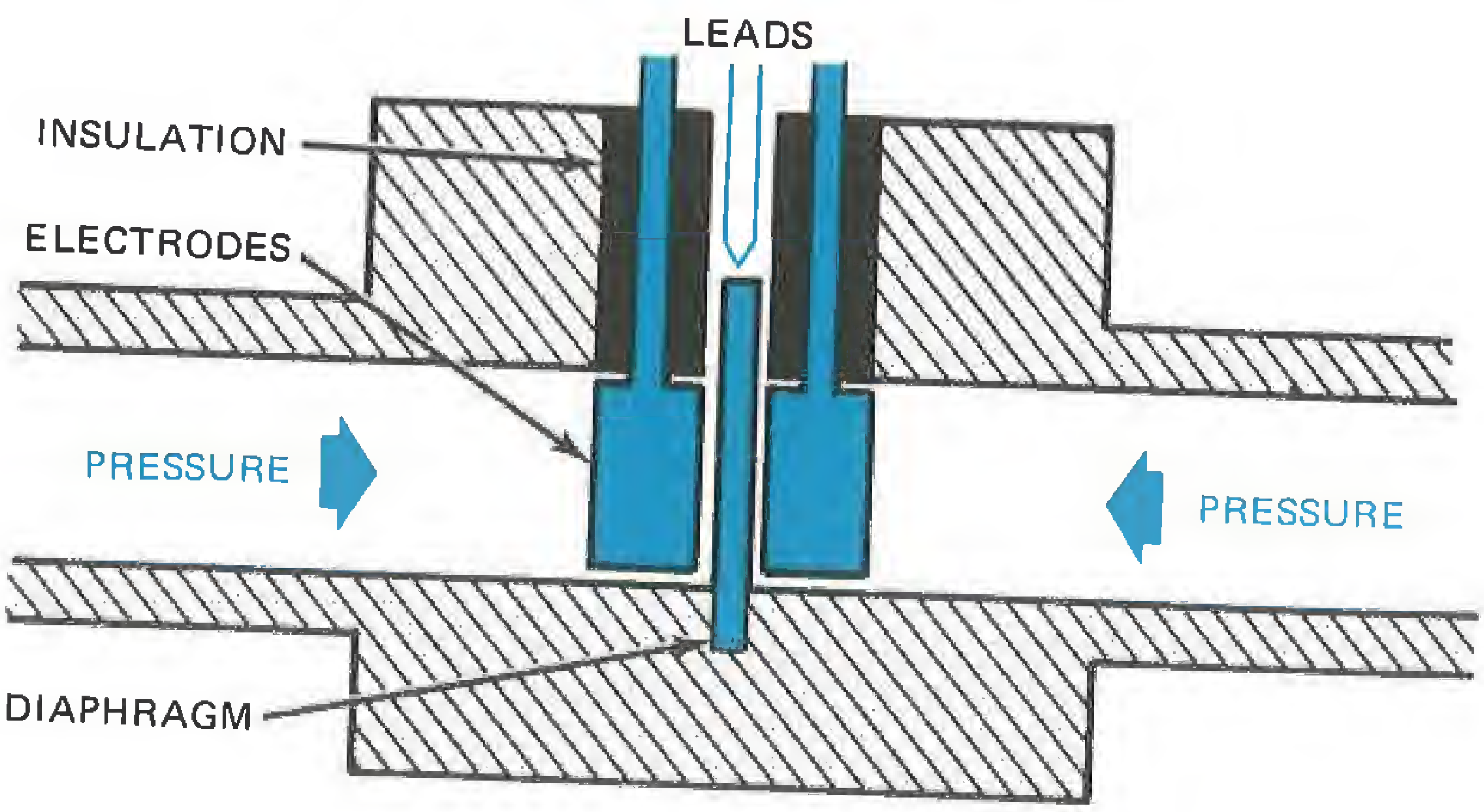


Fig. 8-6 Electrode-Diaphragm Pressure Transducer

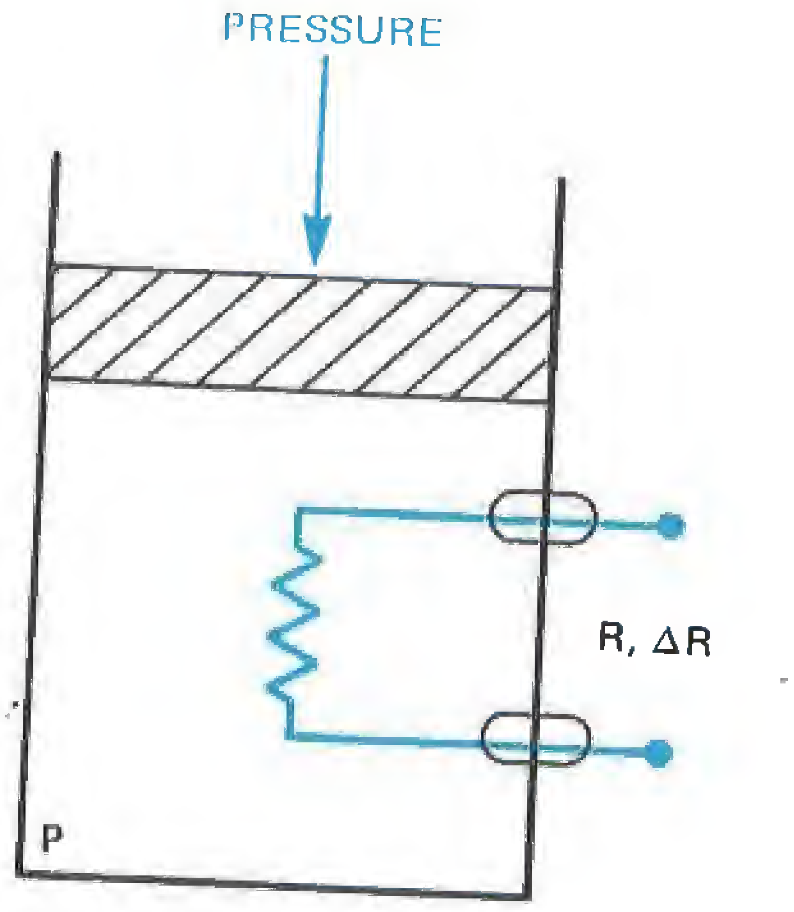


Fig. 8-7 Resistive Pressure Transducer

This transducer is quite unusual in that it operates at a frequency of 20 kHz with an input of 10 volts and a full scale output of 4.5 volts. The nonlinearity of calibration for full-scale output is less than ±1.5 percent.

Because of its small size, it can be placed in the wings or other parts of an aircraft being tested in a wind tunnel. The rise time of this transducer with a 1/8" inlet tube is fairly small, about 40 microseconds.

If a wire is subjected to an external pressure from all directions, as shown in figure 8-7, its electrical resistance will change. The increase or decrease in resistance depends on the type of conductor. The change in resistance is directly proportional to the pressure applied. Mathematically,

$$\boxed{R = R_o(1 + b\Delta P)} \tag{8.6}$$

where

R = resultant resistance

R_o = resistance at one atmosphere pressure

b = pressure coefficient of resistance

ΔP = pressure variation

The table in figure 8-8 shows the pressure coefficients of resistance of some of the more common metals.

Mercury is the preferred metal to use in that it can be produced with uniform purity. But it undergoes a phase transition near room temperature from a liquid to a solid in the pressure range between 6500 and 7600 kg/cm^2.

Metal	Pressure Coefficient b $Cm^2/1\ Kg$	Maximum Deviation From Linearity
Aluminum	-4.0×10^{-6}	-0.001
Cadmium	-9.1×10^{-6}	-0.006
Copper	-1.8×10^{-6}	-0.0004
Iron	-2.3×10^{-6}	-0.0005
Mercury liquid	-22.4×10^{-6}	
solid	-23.6×10^{-6}	
Silver	-3.3×10^{-6}	-0.001

Fig. 8-8 Pressure Coefficients of Resistance b for Selected Conductors

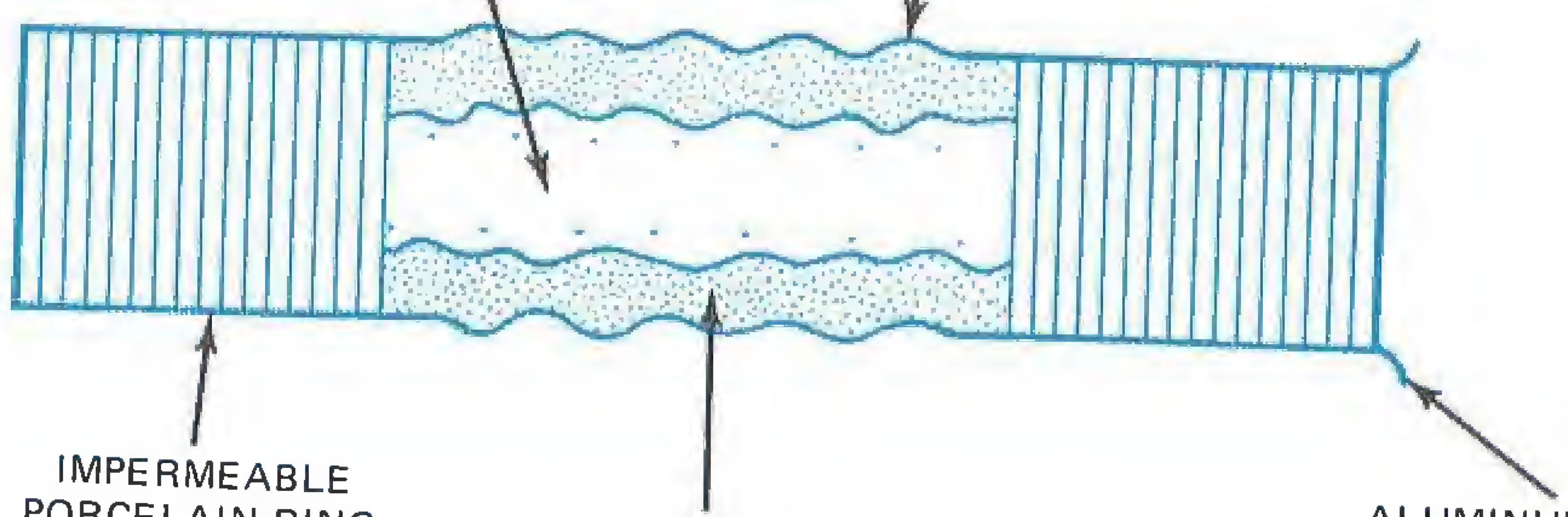


Fig. 8-9 Electrokinetic Pressure Transducer Schematic

The resistive-pressure transducer must be used at a constant temperature since the resistance of the probe varies with temperature.

This transducer is suitable for measuring pressures in ranges from 0 to 10,000 kg/cm^2. The resistance variation follows the pressure variation without time lag or hysteresis. However, if the pressure is transmitted to the transducer by a liquid, a time lag may arise because of the increased *viscosity* of the liquid at high pressure.

The advantage of this transducer over a mechanical gage is its simplicity and ruggedness.

If a liquid, such as water, is brought into contact with a solid body, such as glass, an *electric field* of *molecular* thickness will occur at the interface between the two substances. In this field the glass, as well as some of the water molecules, will acquire a charge. The glass is negatively charged while the water molecules are positively charged. Any movement of the glass particles through the water creates a current, or from the opposite point of view, a movement of the liquid through a stationary *fritted (glass particle) glass disk* gives rise to a potential difference between the sides of the disk. This physical arrangement is known as the electrokinetic pressure transducer as shown in figure 8-9.

If the liquid is pressed through the disk, a potential difference (emf) between the sides of the porcelain disk is present and can be picked up by the two electrodes. Either a constant voltage or an alternating voltage can be picked up depending on the method of the applying pressure. The electrical output and the pressure are directly proportional. The sensitivity is about 350 mV/psi under no load, and 3 μA/psi under short circuit conditions. The output impedance is about 10^5 ohms when the device is shunted by a capacitance of 40 $\mu\mu$F $\pm$ 10 $\mu\mu$F, but can be made to have values up to several hundred megohms.

The corona discharge is the most frequently occurring electric gas discharge form of air pressure and flow-velocity measurement. The system is illustrated in figure 8-10. It consists of a fine needle point electrode and a large electrode which may surround the needle electrode, or it may be a flat or cylindrical electrode located in front of the needle point separated from it by several millimeters. If a high voltage of 1,000 to 5,000 volts is applied, a corona discharge will form in the vicinity of the needle point, and a current of approxi-

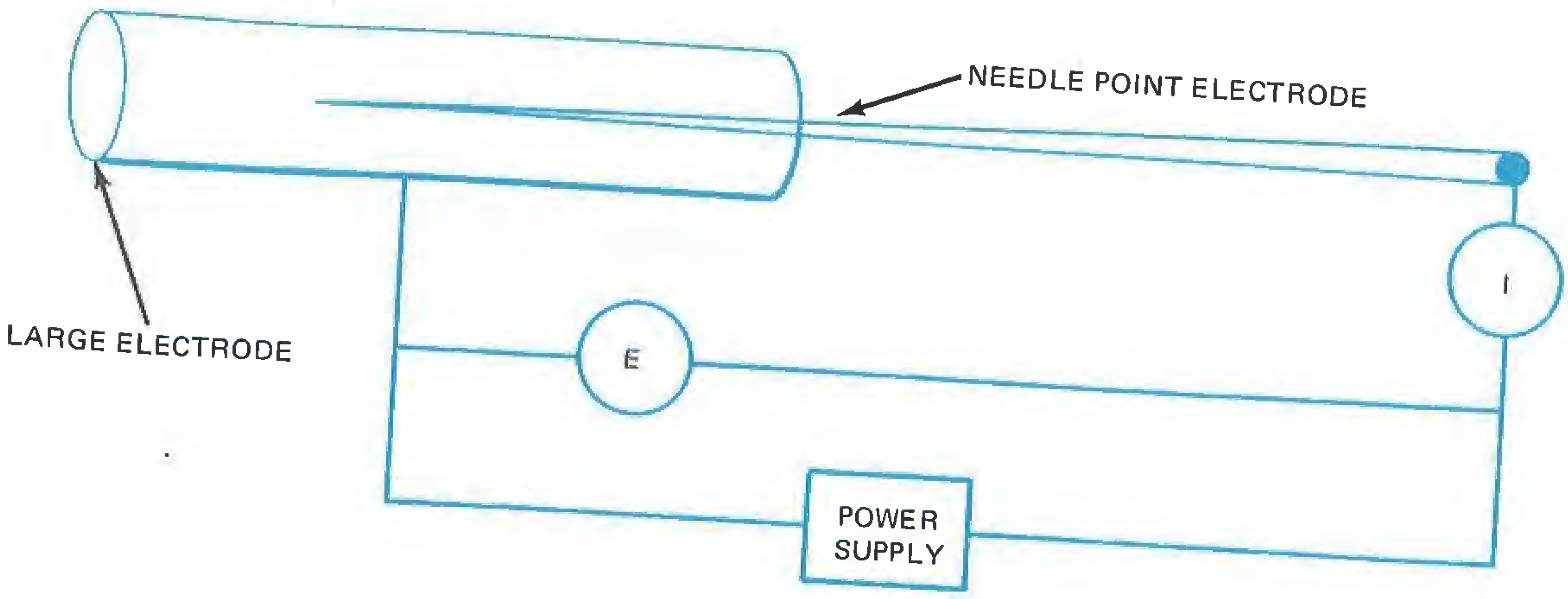


Fig. 8-10 A Schematic of an Electric Gas Transducer

mately 10 microamps can be measured. Typical voltage-current characteristics are shown in the plot of figure 8-11.

The voltage-current characteristics vary for positive and negative polarity of the point and with changes in pressure and gas velocity. The instrument measures primarily the pressure variation in a flowing gas.

The response of this transducer is extremely fast. Other discharge forms such as the flow discharge have been investigated as a means of measuring velocity and pressure.

If certain crystals are exposed to hydrostatic pressure (pressure from all sides), a polarization will develop in the crystal direction. This can produce an output voltage. These transducers are normally high pressure devices, used to measure pressure impulses of several thousand atmospheres, which vary in duration from a second to less than 10 microseconds.

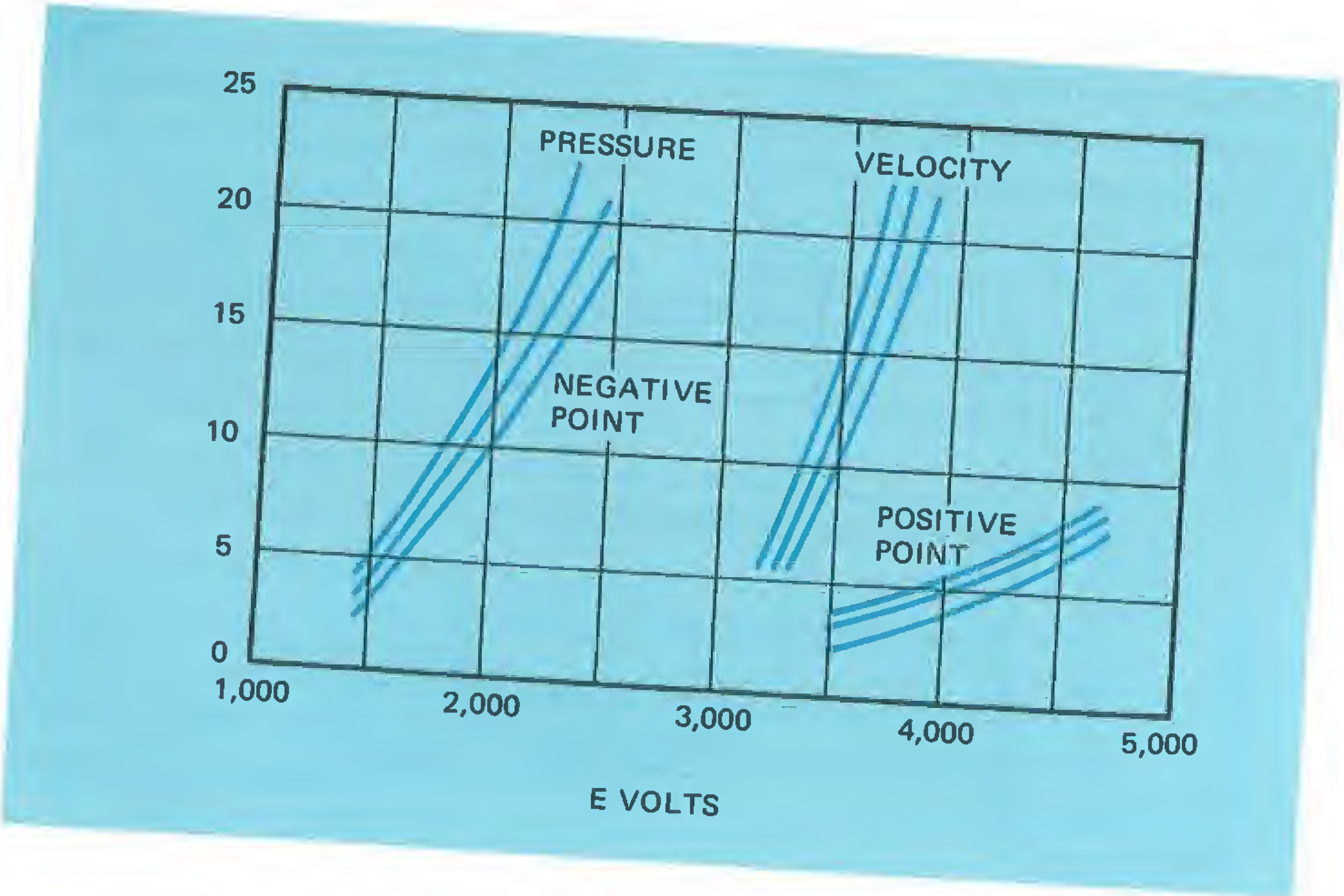


Fig. 8-11 Voltage-Current Characteristics of the Corona Discharge

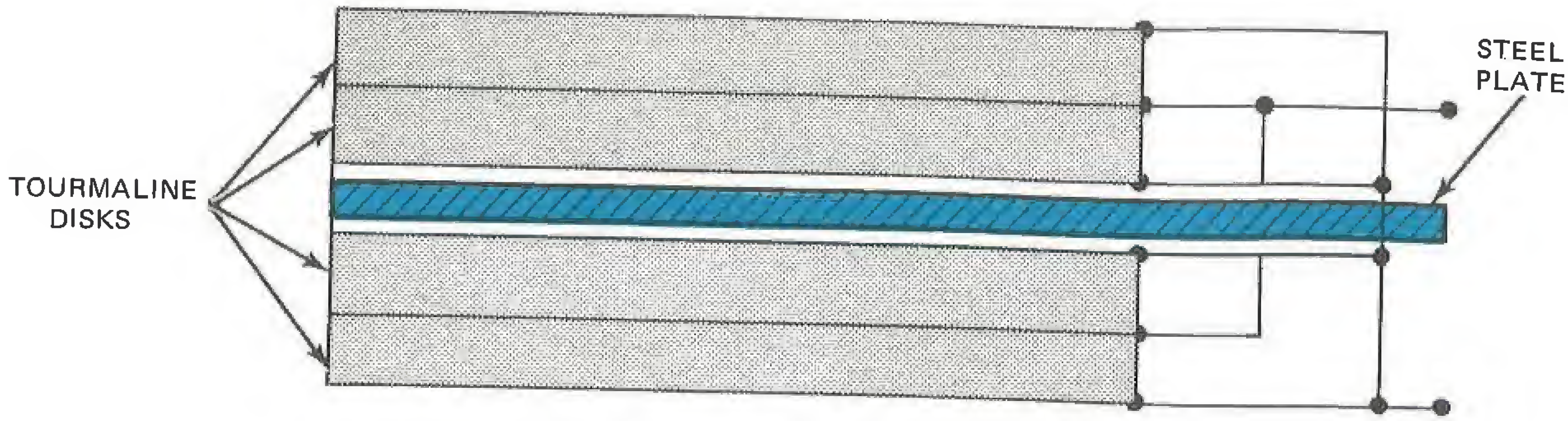


Fig. 8-12 A Schematic of a Piezoelectric Pressure Transducer

Not all crystals are pressure-sensitive, but Tartaric acid, tourmaline, and sucrose have been used as crystals for pressure transducers. Tartaric acid has a sensitivity of 21×10^{-12} coulombs per psi, tourmaline has a sensitivity of 11×10^{-12} coulombs per psi, and sucrose has a sensitivity of 5.6×10^{-12} coulombs per psi. The output voltage is normally a linear function of the pressure.

The piezoelectric pressure transducer schematic shown in figure 8-12 consists of four circular tourmaline disks stacked on both sides of a steel plate. These disks are coated with a conductive material and connected to the terminals. The entire assembly is then coated with an insulating material. Gages of this type are capable of measuring pressures ranging from 0.5 to 100,000 lb/in.^{2}.

Because of the small size of this type of pressure transducer, the distortion of the pressure field is usually negligible. Some other characteristics of this type of transducer are: high output impedance, dynamic response which falls off at low frequencies, and spurious outputs with temperature variations. This latter type of output is called the pyroelectric effect.

Piezoelectric cyrstals are used in high-frequency accelerometer transducers because of their high output voltage and wide frequency response. Because the piezoelectric crystal is inherently a dynamic-responding sensor, it is better for this type of activity than for steady-state conditions. Figure 8-13 shows a schematic of one type of acceleration transducer.

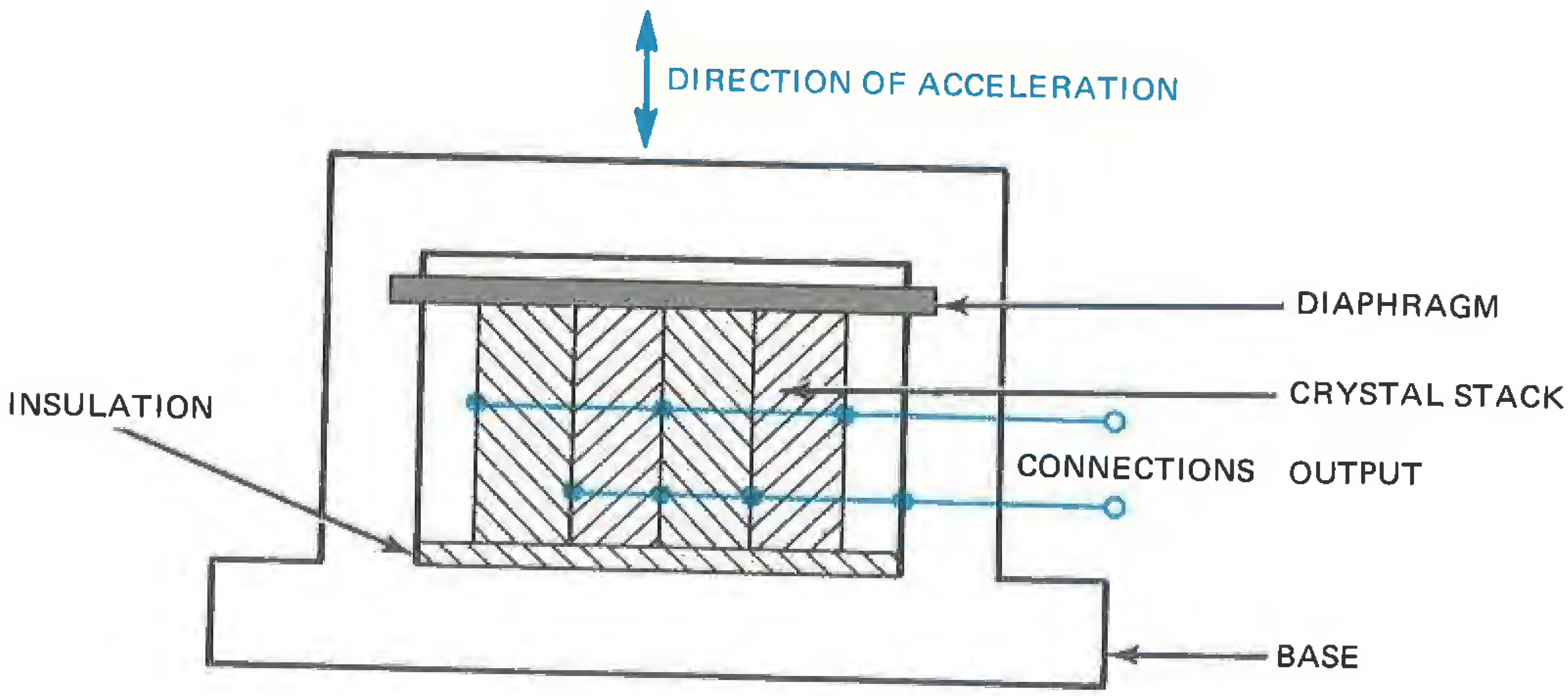


Fig. 8-13 Schematic of an Acceleration Transducer

	Minimum Range	Maximum Range
Diaphragm	0″ to 2″ water	0 to 400 psi
Bellows	0″ to 5″ water	0 to 800 psi
Capsule	0″ to 1″ water	0 to 50 psi
Bourdon Tube	0 to 12 psi	0 to 100,000 psi
Spiral	0 to 15 psi	0 to 4,000 psi
Helix	0 to 50 psi	0 to 10,000 psi

Fig. 8-14 Limits of Pressure Elements

According to Newton's basic law of motion

Force (f) = mass (m) X acceleration (a) **(8.7)**

When the accelerometer is moved as indicated in figure 8-13, a force is applied to the piezoelectric material which, in turn, produces a voltage. Through equation 8.7, one can see that the force applied is a direct function of the acceleration, because the mass is a constant.

There are many types of pressure transducers that are not mentioned in this experiment. There are also other actuator devices that might be employed besides the diaphragm and bellows shown in this discussion. Some of these devices change shape when pressure is applied and are known as elastic deformation pressure elements. Each of them is adaptable to a different pressure range. Among these are the capsule, bourdon tube, spiral and helix. The table in figure 8-14 gives the upper and lower limits of pressure which can be applied to each device in inches-of-water or in pounds per square inch.

The transducers mentioned thus far are used primarily for measuring or sensing pressures and translating the pressure into an electrical output. Frequently, instead of measuring just one pressure, it is important to measure the difference between two pressures. This is known as differential pressure measurement.

Differential pressure measurement is not too far removed from single pressure measurement. In fact, the same instruments can be used. The U-tube manometer is a device used in measuring both pressure and pressure difference.

The U-tube manometer consists of a glass tube shaped like the letter U with a scale marked in inches on the tubes. Figure 8-15 illustrates such a device.

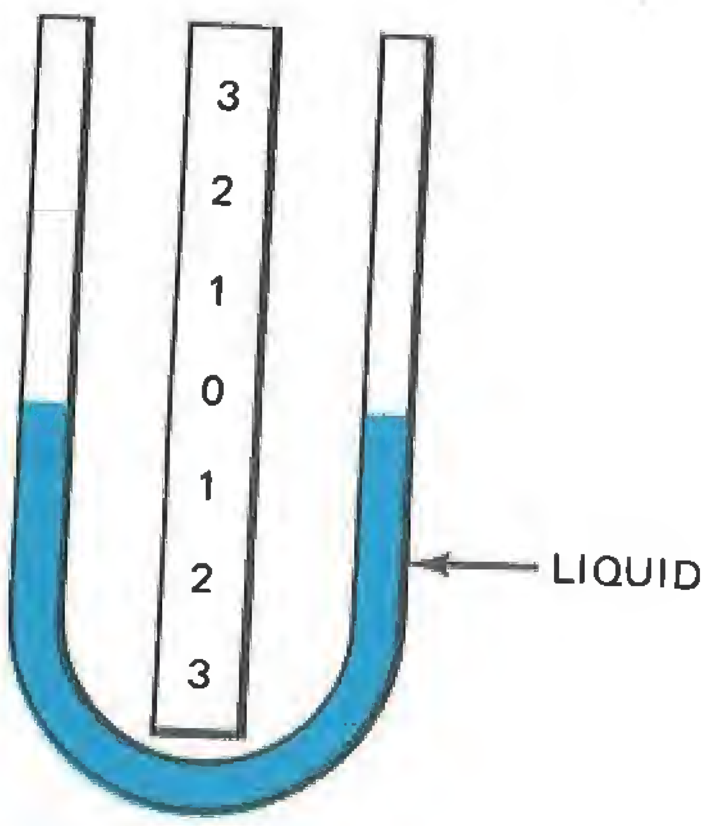


Fig. 8-15 A Simple U-tube Manometer

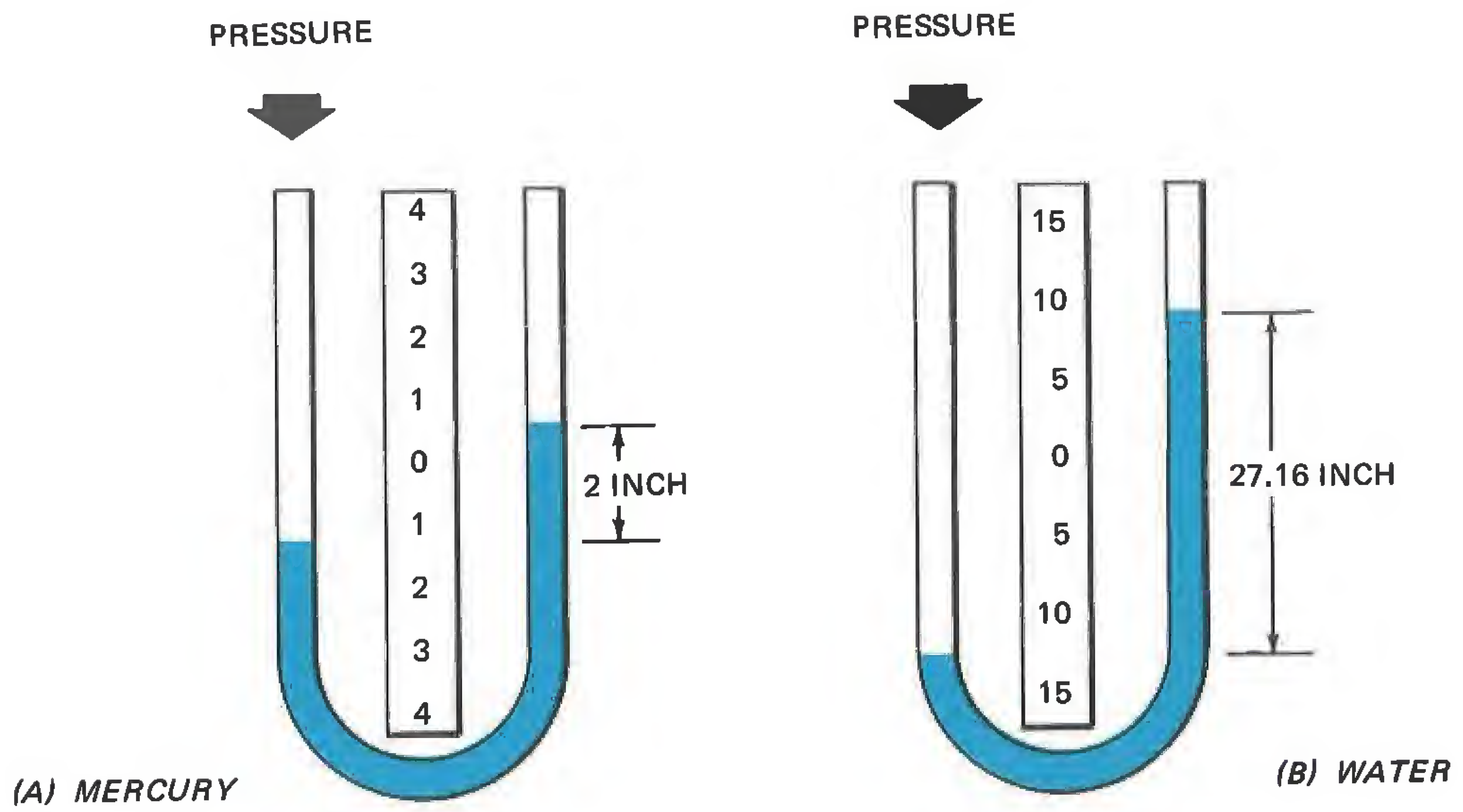


Fig. 8-16 Liquid Level Change from the Example

On the scale the zero is located at the center. When both tubes are open to the atmosphere, the level of the liquid (usually water or mercury) will be at the zero mark in both tubes. When pressure is forced into one side of the manometer, the liquid in that side will go down causing the level in the other tube to rise. The liquid changes levels because the pressure is exerted by the atmosphere on the open side. The difference in pressure causes the liquid level to adjust to the new pressures. By measuring the difference in the height of the fluid in the two columns, the pressure can be expressed in inches of the fluid.

For example, if a pressure was applied on one side of the manometer in figure 8-15 and the liquid moved down one inch in one column and up one inch in the other column, there would be a total of two inches displaced. If the liquid was mercury, this would be referred to as two inches of mercury. The corresponding pressure would be 0.98 pounds per square inch because one psi corresponds to 2.04 inches of mercury or 27.7 inches of water. If water was the liquid, the water height change in each tube with the pressure above would be 13.58 inches or an over-all change of 27.16 inches. Figure 8-16 shows the change in liquid for both water and mercury.

When the U-tube manometer is used with one tube left open to the atmosphere, the pressure indicated represents a uni-directional pressure measurement instrument. If both columns of the manometer are connected to separate pressures, a bi-directional pressure measurement instrument is developed, and the indicated pressure is the difference in the uni-directional and bi-directional pressure measuring manometers.

To actually use this kind of device to transduce pressure to some other form of energy, the well-type manometer is used. In this type of instrument the manometer is made of metal and is attached to the instrument case. Instead of reading the height of the liquid in the column, a float in one column moves up and down, driving the wiper of a potentiometer. The movement of the wiper represents linear motion which can

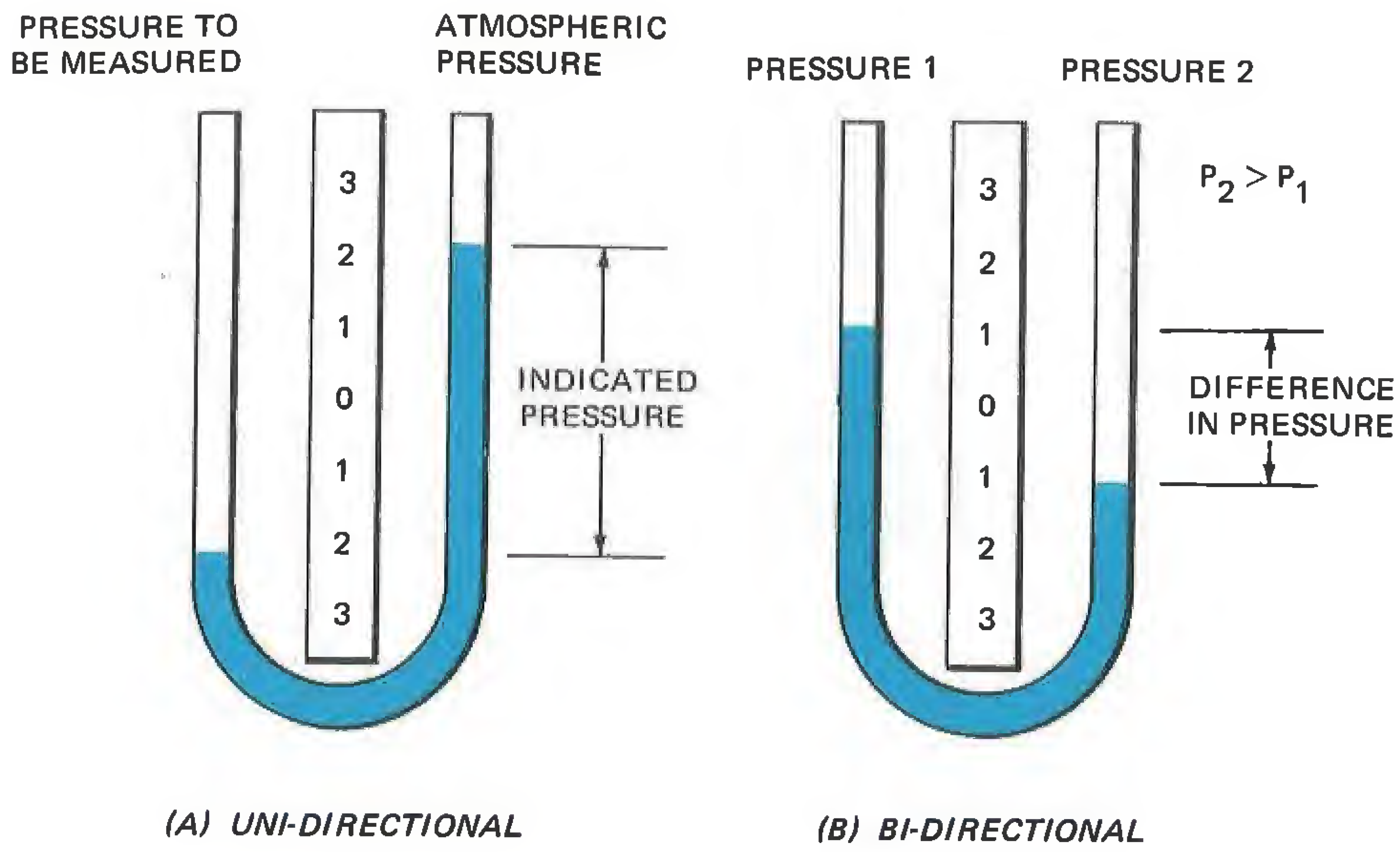


Fig. 8-17 Unidirectional and Bidirectional Pressure Measurement Manometer

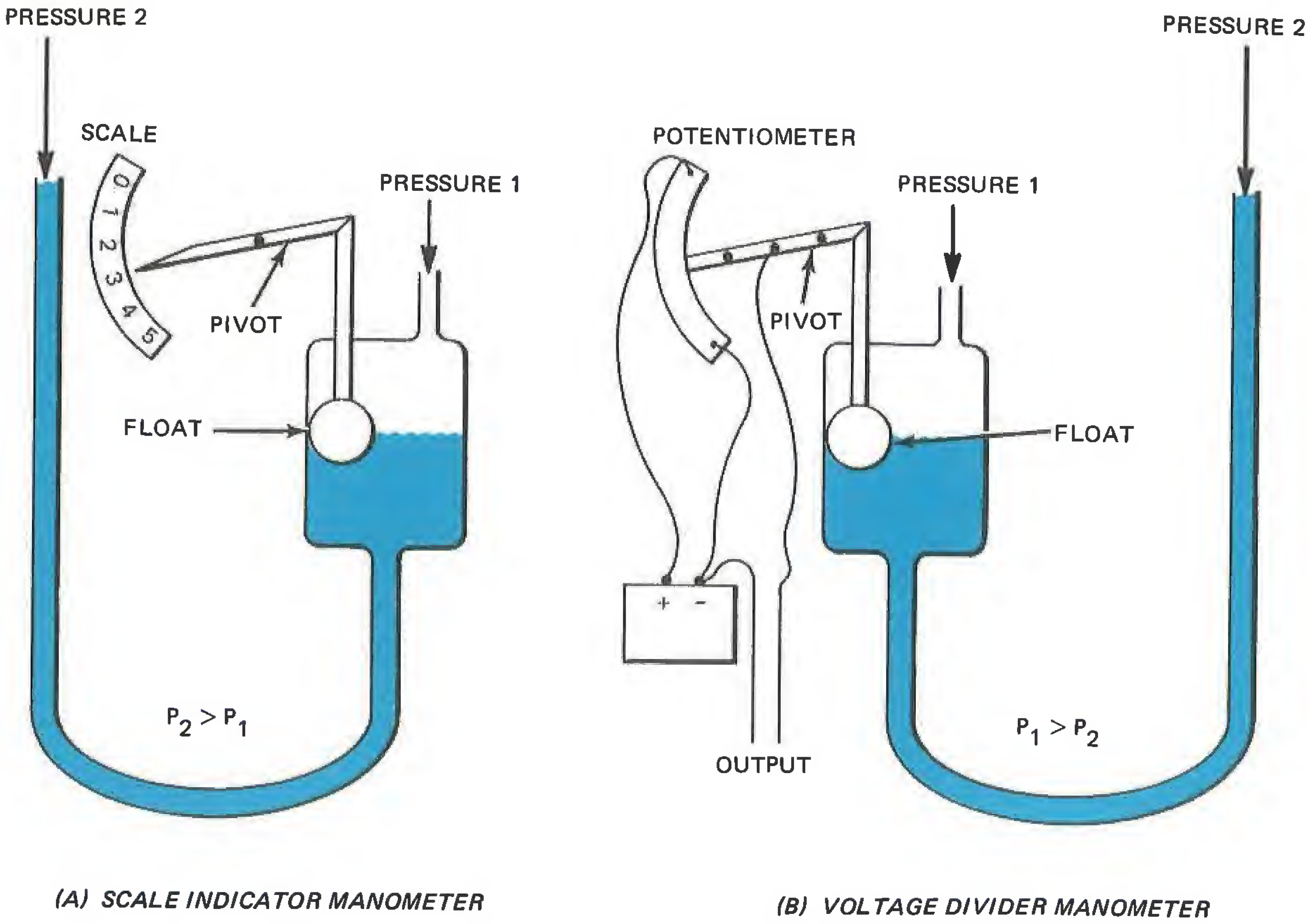


Fig. 8-18 Well-Type Manometer

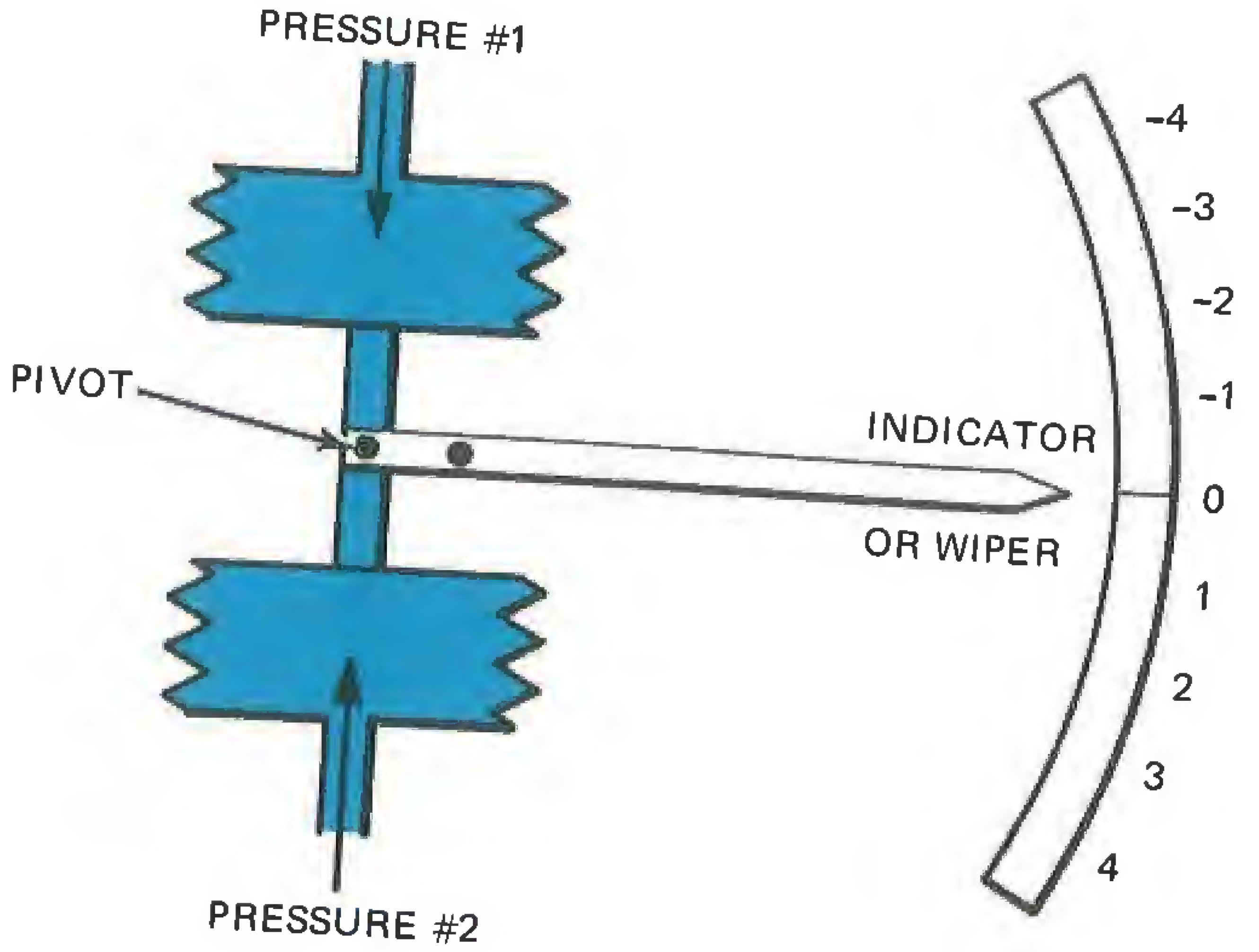


Fig. 8-19 Bellows-Type Differential Pressure Measuring Equipment

be calibrated to indicate the pressure change or differential pressure depending on the application of the device.

If the movement of the float drives a wiper on a potentiometer, a voltage divider can be used to start a pump on one side of the line to readjust the pressure.

The mechanism used to transfer the float height to the outside indicator must be as friction-free as possible to have an accurate and precise instrument. Figure 8-19 shows the well-type manometer.

Another differential pressure measuring instrument makes use of two matched bellows on a common shaft. Each bellows has its own input pressure. The difference in pressure causes one bellows to become more deformed than the other. This difference causes movement of the common shaft.

As with the manometer float, a pressure bearing or torque tube is used to transfer the bellow's motion from the inside to the outside of the meter body. Figure 8-19 shows a simplified schematic of the bellows-type differential pressure measuring instrument

For uni-directional pressure reading, pressure number one could be open to the atmosphere. All pressures above atmospheric applied at pressure number two would cause a change in the indication by the movement of the common shaft.

For bi-directional pressure reading, pressures number one and two would be different, and the indicator would move in a direction depending on which one was greater.

MATERIALS

1 Air supply
2 Air regulators
3 Pressure gages 0-30 psi
2 Check valves
2 Flow control valve
1 U-tube manometer, approximately 16 inches long
1 Supply of hydraulic oil
1 Cross connector
2 Tee connectors
Various lengths of air hoses and connectors

PROCEDURE

1. Connect the pneumatic system shown in figure 8-20.

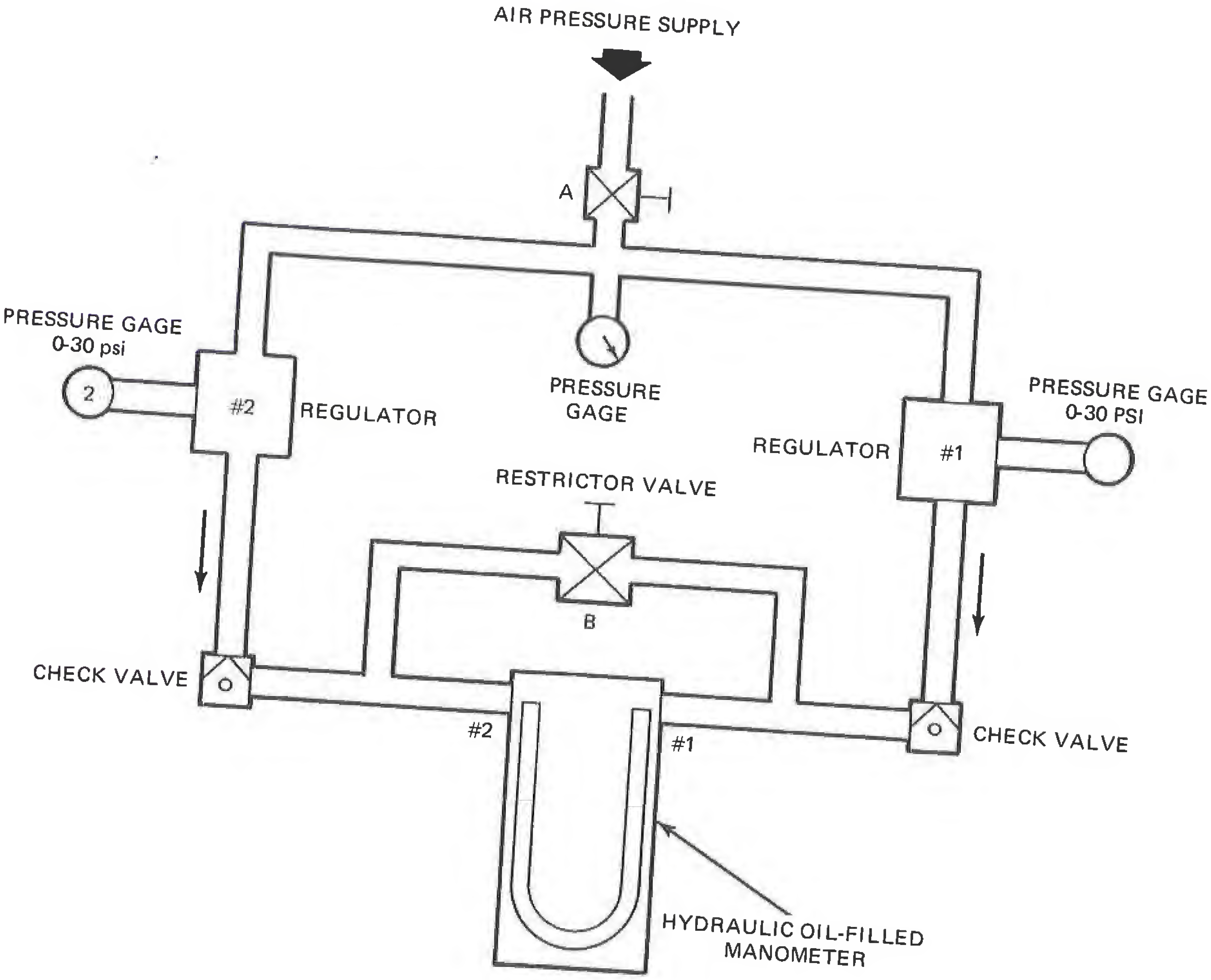


Fig. 8-20 Experiment System

2. Fill the manometer with the hydraulic fluid so that the level is half way up the tubes. Clamp it to a stand in such a way that it is held upright and will not fall or break.
3. Attach a clean sheet of paper over the scale.
4. With no pressure on the system, both tubes should show equal levels of fluid.
5. With B closed and the regulators open, slowly increase the supply pressure so that about 20 psi is in the system.
6. Without regard to what happens in the manometer, slowly close the regulators, both at the same time, until 10 psi is indicated on gages one and two.
7. If both gages are reading the same pressure, the level of liquid should be equal.

8. If not, slowly adjust regulator number two until the levels are equal. When this is done note the value indicated on the gages. What you are doing is actually calibrating the gages to read equal pressures, not necessarily the correct pressure. What is important is that the pressures are equal. Pressure gage one needs to be the one that reads the lower of the two when the levels are equal. If this is not the case, exchange the gages because gage one is to be the reference pressure. Record the difference in pressure reading when the levels are equal so it can be held constant throughout the experiment. Gage number two reads 10 psi +_______psi when gage number one reads 10 psi.
9. Allow the fluid to drain down from the upper part of the tubes.
10. Mark the level of liquid and record it as zero.
11. With regulator number one set so that gage number one reads 10 psi, slowly increase the pressure to side two of the manometer. You will probably notice the liquid level rising to the top of side one with very little pressure change.
12. To relieve this condition slowly open the restrictor valve B. You should notice that the level of liquid in side one goes down.
13. Continue adjusting both regulator number two and valve B until gage two reads 15 or 16 psi with the liquid all the way to the top of side one; or until valve B is all the way open.
14. When step 13 is completed, mark the level of the liquid on side one and record the corresponding pressure difference between gage one and gage two. Remember the correction factor from step 8. **Do not change the opening of valve B again.**
15. Decrease the pressure in side two by one psi. Mark the level and record the pressure.
16. Repeat step 15 until zero pressure difference is recorded and the levels are again equal.
17. Increase both regulators slowly until gage one reads 15 psi and the levels of liquid are equal.
18. With pressure one at 15 psi, increase pressure two by one psi. Note the level of the liquid in side one. Mark the level and indicate the pressure difference on the same paper as used before. They should show approximately the same thing.
19. Repeat step 18 for all pressure differences recorded in the first part of the experiment.
20. When step 19 is completed the uni-directional part of the experiment is completed. Note that your recorded values only show the pressure above the reference pressure set by regulator 1.
21. Attach a clean sheet of paper over the scale.
22. Start the bi-directional experiment with 15 psi on gage 1 and the liquid levels equal.
23. Valve B should not have to be adjusted for this part of the experiment.
24. Increase pressure 2 one psi. Mark the liquid level on side 1 and record the pressure difference.

25. Repeat step 24 until the liquid is at the top of the manometer. Mark all levels and record all pressure differences as **plus** values.
26. Decrease pressure 2 until the levels are equal.
27. Decrease pressure 2 one psi. Mark the level on side 1 and record the pressure differences as **minus** values.
28. Repeat step 27 until the level of liquid in side 2 is at the bottom of the manometer.
29. Note that the scale indicates pressure differences both above and below the set point.

ANALYSIS GUIDE. From the experiment it should be apparent that the uni-directional and bi-directional pressure measuring devices can perform different functions. Explain how these two devices could be used as transducers indicating pressure differences in fluid systems. Plot graphs of distance versus pressure from the calibrated scales.

PROBLEMS

1. What was the purpose of using the restrictor valve B in the experiment?
2. What analogy to electric circuits can be made for the following parts of the pneumatic circuit: air pressure supply, pressure regulators, pressure gages, check valve, restrictor valve, restrictor valve circuit B, U-tube manometer and the pneumatic hose.

experiment 9 MEASUREMENT OF DENSITY & SPECIFIC GRAVITY

INTRODUCTION. In industrial processes and engineering work it is frequently desirable and often necessary to know the *mass density*, *weight density*, or *specific gravity* of a material. In this experiment we will investigate the difference in measuring density and specific gravity.

DISCUSSION. If small cubes of different materials having the same volume are weighed, it may be found that all of the materials obtained have different weights. Aluminum is considerably lighter than most other metals, whereas lead is one of the heaviest metals. The weight of substances such as wood, rubber, and plastic is less than most metals.

In order to compare the relative heaviness of different substances, the term *density* is used. Because of its availability, water is usually used as the basis for comparison. Because of volumetric changes, the temperature must be specified. Since water has its great density at 39°F, the comparison scales of densities are developed for that temperature.

Liquids also have different weights for the same amount of volume. Figure 9-1 shows different liquids of equal volume in the same container. The level at which each liquid is suspended is determined by its weight.

In technical work "mass density" refers to *the mass of an object per unit volume.* In the English system, mass density is defined in slugs per cubic foot and is identified by the greek letter rho. The equation for mass density is

$$\boxed{\rho = \frac{m}{V}} \qquad (9.1)$$

where ρ = mass density, slugs per cubic foot
m = mass, slugs
V = volume, cubic feet

On the other hand, weight density is defined as *the weight force per unit volume* and is symbolized by the letter w. The equation for weight density is

$$\boxed{w = \frac{W_f}{V}} \qquad (9.2)$$

where w = weight density, pounds per cubic foot
W_f = weight force, pounds
W = volume, cubic feet

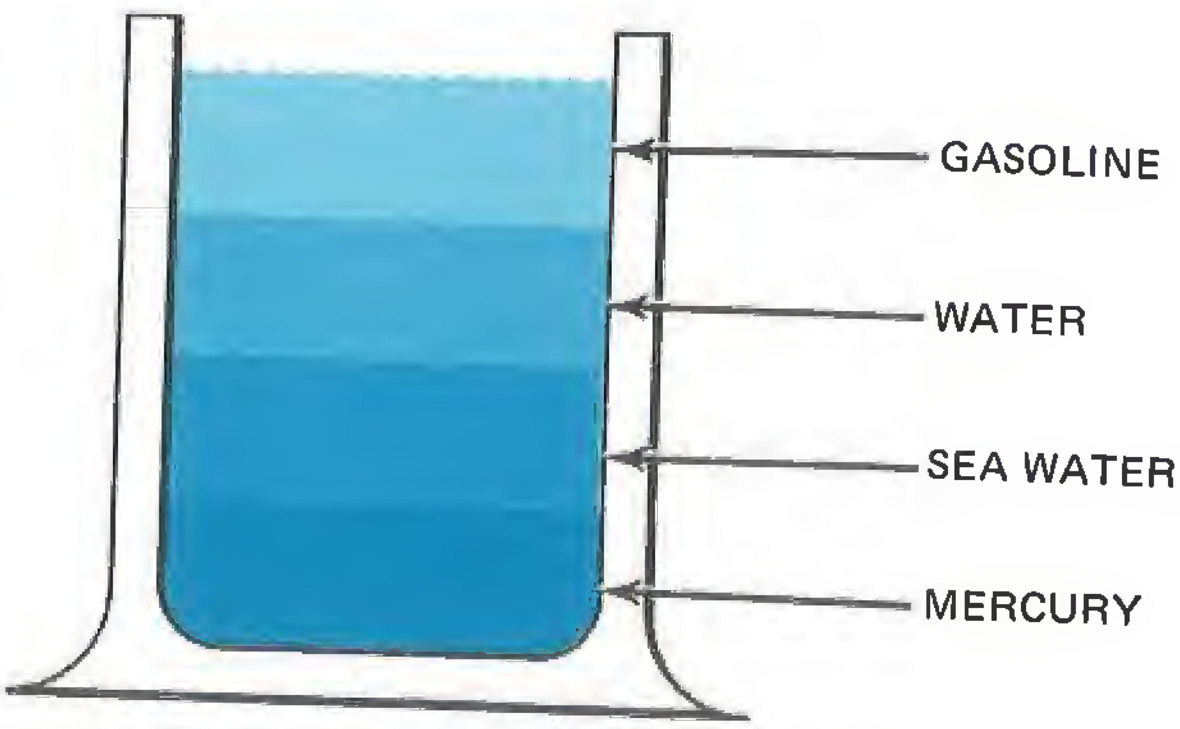


Fig. 9-1 Comparison of the Weights of Liquids

By Newton's Law, the mass and force are proportional to the acceleration:

$$\boxed{F = ma \text{ or } m = \frac{F}{a}} \qquad (9.3)$$

where a can be acceleration due to gravity, g. Through equation 9.3 the mass density and weight density can be equated. Since weight is the force exerted on a given mass by the gravitational effect of the earth,

$$\text{weight density} = \text{mass density} \times \text{acceleration of gravity} \qquad (9.4)$$

$$w = \rho g$$

The dimensions of ρg are the same as for the weight density.

When a body is weighed on a beam balance it is directly balanced by a known and calibrated weight. This operation is actually determining the mass of the body because the attraction of gravity on both unknown and known masses is assumed to be the same. However, if a mass is weighed on a spring scale the deflection of the scale will be influenced by the local value of the earth's gravitational attraction. The weight of the body is dependent upon this attraction of gravity, whereas the mass of the body is not.

Specific gravity is defined as *the ratio of the mass or weight density of a substance to the mass or weight density of a selected reference material such as water under the prescribed conditions of constant volume and temperature.* The ratio is given as

$$\boxed{\text{Sp gr} = \frac{\rho}{\rho_W} = \frac{W}{W_W}} \qquad (9.5)$$

where ρ_W = mass density of water

W_W = weight density of water

In order to find the density of a block of wood or metal, it is necessary to find the weight of the block and its volume. The weight can be found by means of an ordinary balance whereas the volume can be found by measurement.

Another method for determining specific gravity is to weigh a given volume of material and then find the weight of an equal volume of water. The ratio of the weight of the material to that of water gives the specific gravity of the material.

An instrument which is used to find the density or specific gravity of a liquid is called a hydrometer. The most common hydrometer consists of a glass float which is weighted at the bottom. The float has a stem which has a graduated scale. To find the density of the liquid, the hydrometer is floated in the liquid and the position of the surface of the liquid on the hydrometer scale indicates the density. This device is shown in figure 9-2.

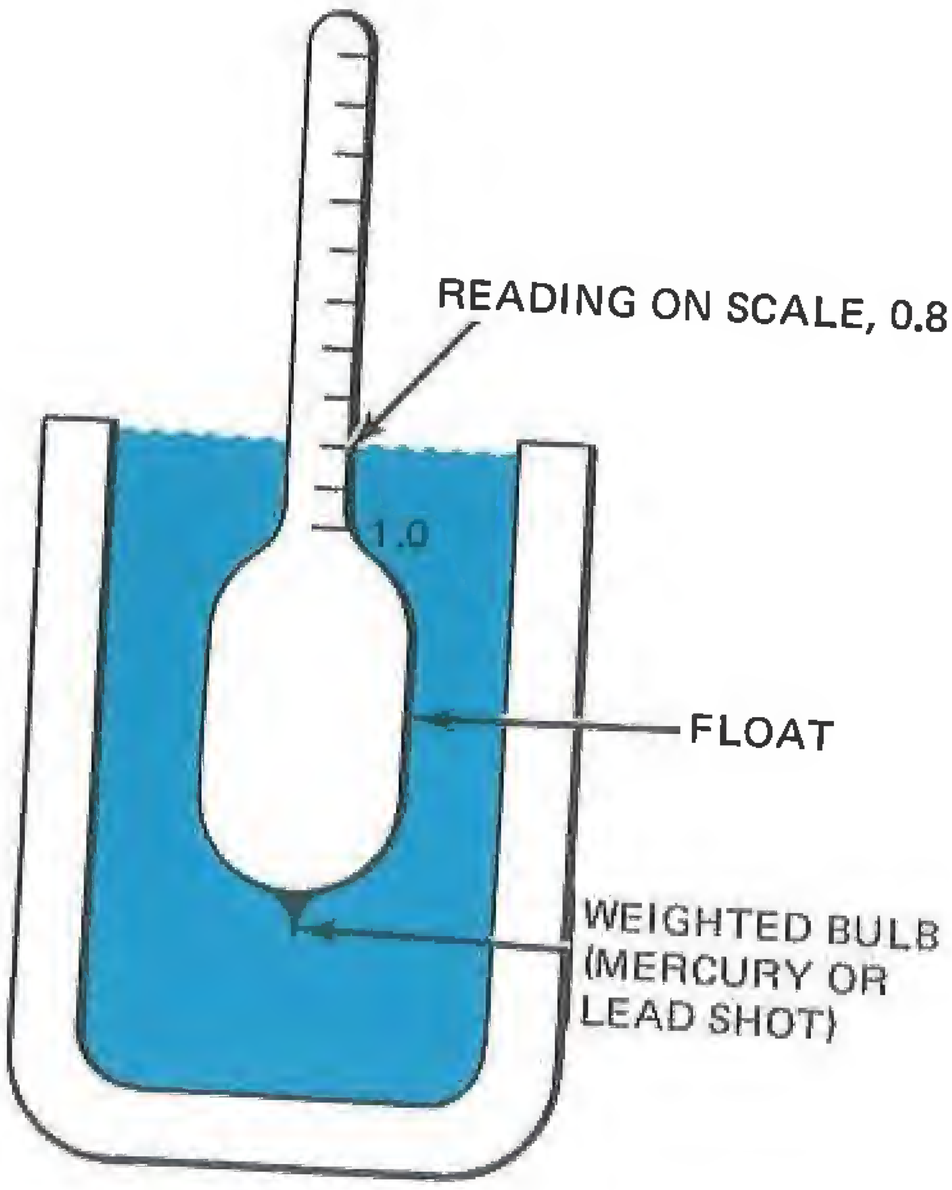


Fig. 9-2 Simple Hydrometer

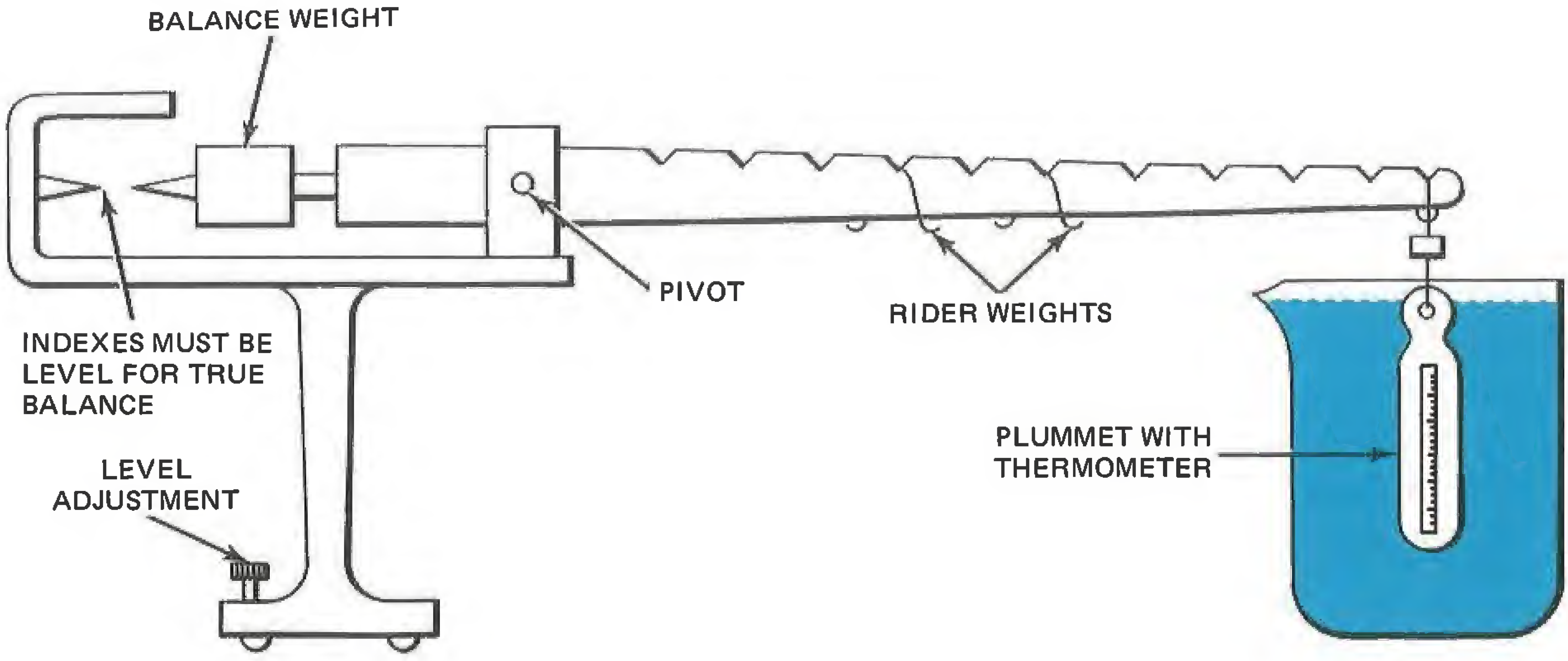


Fig. 9-3 Westphal Balance

The hydrometer is based on Archimede's principle of floatation, which states that *the weight of a floating object is equal to the weight of the fluid which it displaces.* The float increases the buoyancy of the hydrometer because of the liquid displaced. Hydrometers which are used for liquids lighter than water have a large float and the scale graduation starts with a specific gravity of 1.00 at the top.

Hydrometers are used in industry for testing liquids such as salt solutions, petroleum products and acids. To test the specific gravity of the acid solution in the storage battery, a storage-battery hydrometer is used. The value obtained can be used to indicate the degree to which the battery is charged. Hydrometers are also used in the testing of antifreeze mixtures, of milk for possible dilution, and for estimating the strength of wines and beers.

As pointed out above, if a body of constant volume is immersed in a liquid, the corresponding loss of weight of the body is proportional to the weight of an equal volume of the liquid. If two liquids are used, one of which is water, the specific gravity of the unknown liquid may be found.

The Westphal balance shown in figure 9-3 is an instrument used in the laboratory to determine the specific gravity of an unknown liquid. The instrument is standardized with distilled water. Special beam-rider weights are used to accurately balance the instrument. When the indexes are completely level, the correct amount of weight is on the beam. When the plummet is fully immersed in the liquid under test, the specific gravity of the unknown liquid can be read directly by adding up the beam-rider weights. Accurate results can be obtained with this balance if great care is taken.

The plummet displaces five grams of distilled water at 20°C. Therefore, a five-gram weight is suspended from the same loop as the plummet when testing distilled water. The balance should be in equilibrium, thus indicating a specific gravity of 1.000. The

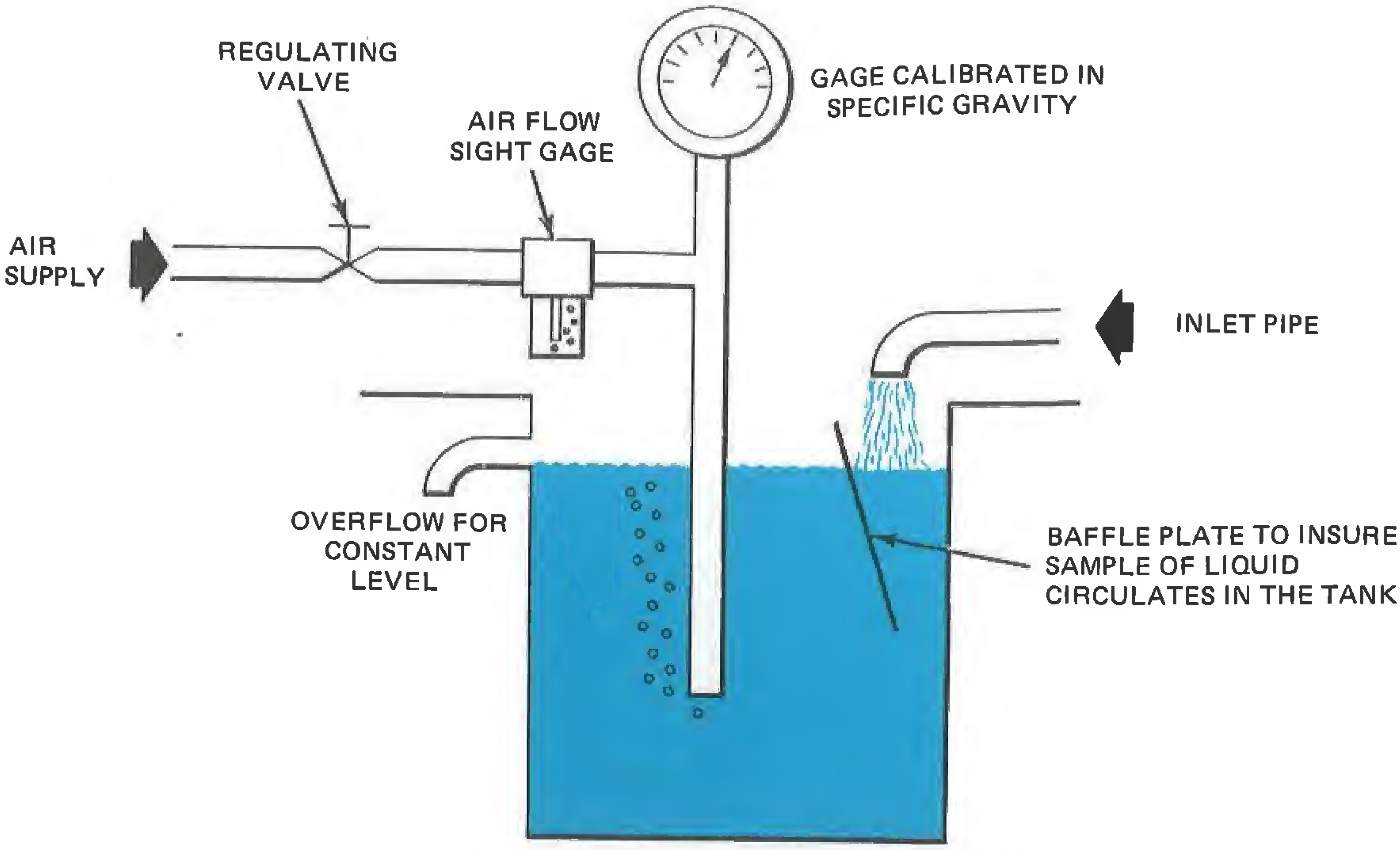


Fig. 9-4 Bubbler System Used to Measure Specific Gravity

five-gram rider is left in the same position for liquids which are heavier than water, and it is removed and used on the beam for liquids which are lighter than water. The riders are used one at a time in order of decreasing weight. If a five-gram rider is in notch 6, a five-gram rider in notch 5, a 0.05 gram rider in notch 3, and a 0.005 gram rider in notch 1, the specific gravity is read as 0.6531.

To measure density and specific gravity in industry, a number of methods are used. One method is known as an air bubbler method. This arrangement is shown in figure 9-4. This method necessitates drawing a sample of the liquid from the process system. A standpipe is immersed into a container of constant depth. Air is fed past a regulating valve and a sight gage into the standpipe. Bubbles are just permitted to escape from the bottom end of the standpipe. This shows that the pressure in the system and the standpipe is equal to the pressure due to the head of liquid above the lower end of the pipe. This pressure will vary with the specific gravity of the liquid, and the indicating instrument is calibrated in terms of specific gravity. The air pressure, in pounds per square feet, equals the pressure head of liquid in the same units. This is given by

$$p = h \times 62.4 \times \text{sp. gr.}$$

where

p = pressure of the air in the system and standpipe, lb/ft^2

h = height of liquid above the opening at the bottom of the standpipe, ft.

sp. gr. = specific gravity of the liquid

62.4 = weight density of water in lb/ft^2

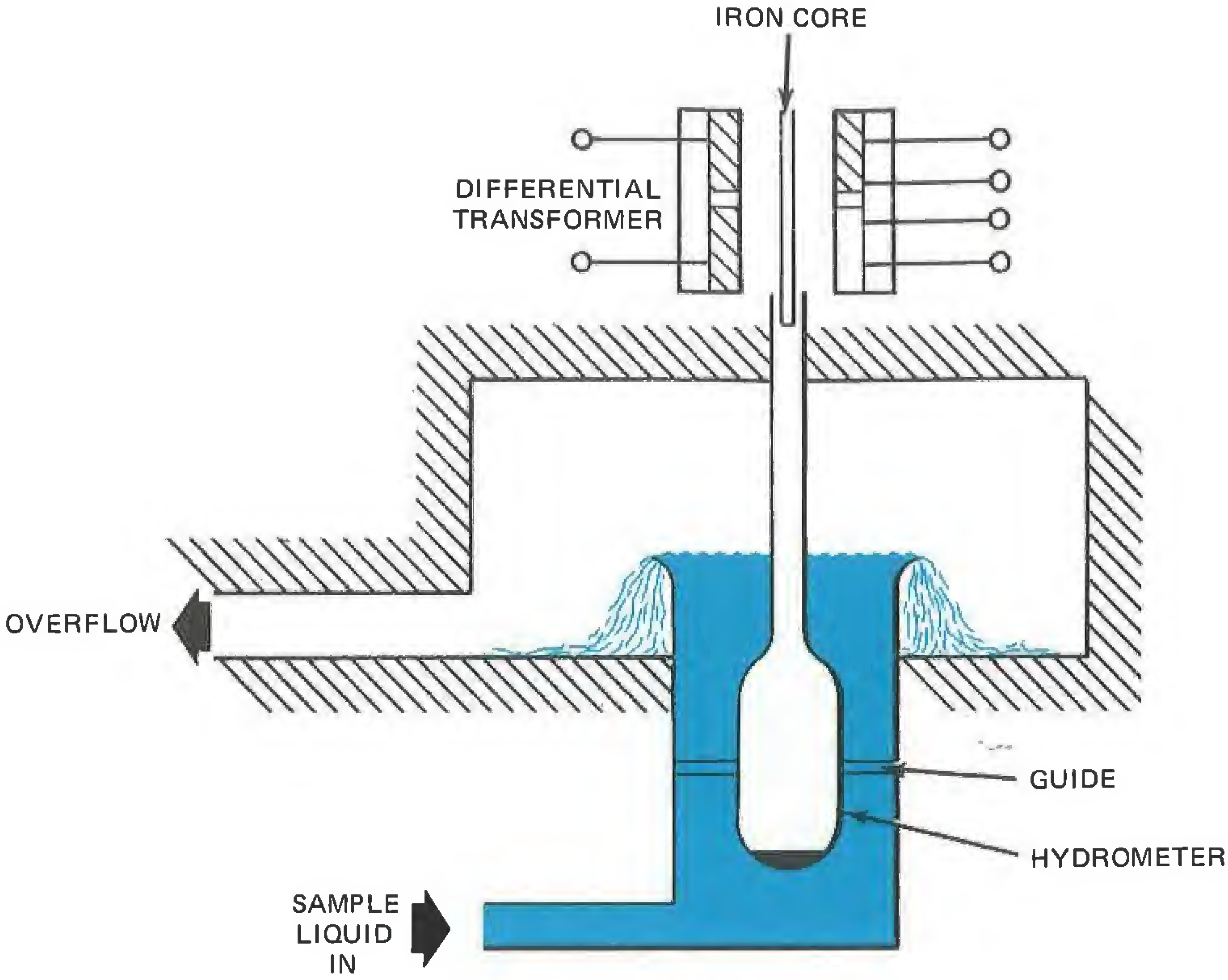


Fig. 9-5 Electrical Recording Hydrometer

There are many designs of electrical recording specific gravity meters that are used in industry. The electrical recording hydrometer is one of them. The hydrometer is contained in a glass cylinder in which the overflow sill and outlet maintain a constant liquid level. This arrangement is shown in figure 9-5.

At the top of the hydrometer is a length of iron which is used as the core for a differential transformer containing two equal secondary windings. As the density of the particular fluid under study varies, the hydrometer will change the position of the iron core of the transformer. By changing the core position, the ratio of the transformer outputs in the secondary will change. A circuit can be set up to indicate or record the change in the voltages of the secondary windings. The indicating instrument could be calibrated in either density or specific gravity units depending on the application.

In figure 9-6 a particular type of measuring and controlling meter used with clear liquids and industrial slurries is shown.

The liquid under measurement flows through a hairpin loop of tube A. Tube A pivots about the axis BB where there are flexible connectors C. The weight of the tube and the fluid within is transferred to the beam D and is balanced by the counterweight E. A change in the density of the fluid disturbs a state of equilibrium which is detected by the force balance F, the output of which is proportional to the change in density. The rider G is moved to adjust the sensitivity. A calibrated weight H, hung on the beam, permits the sensitivity to be verified. The rate of flow does not affect the

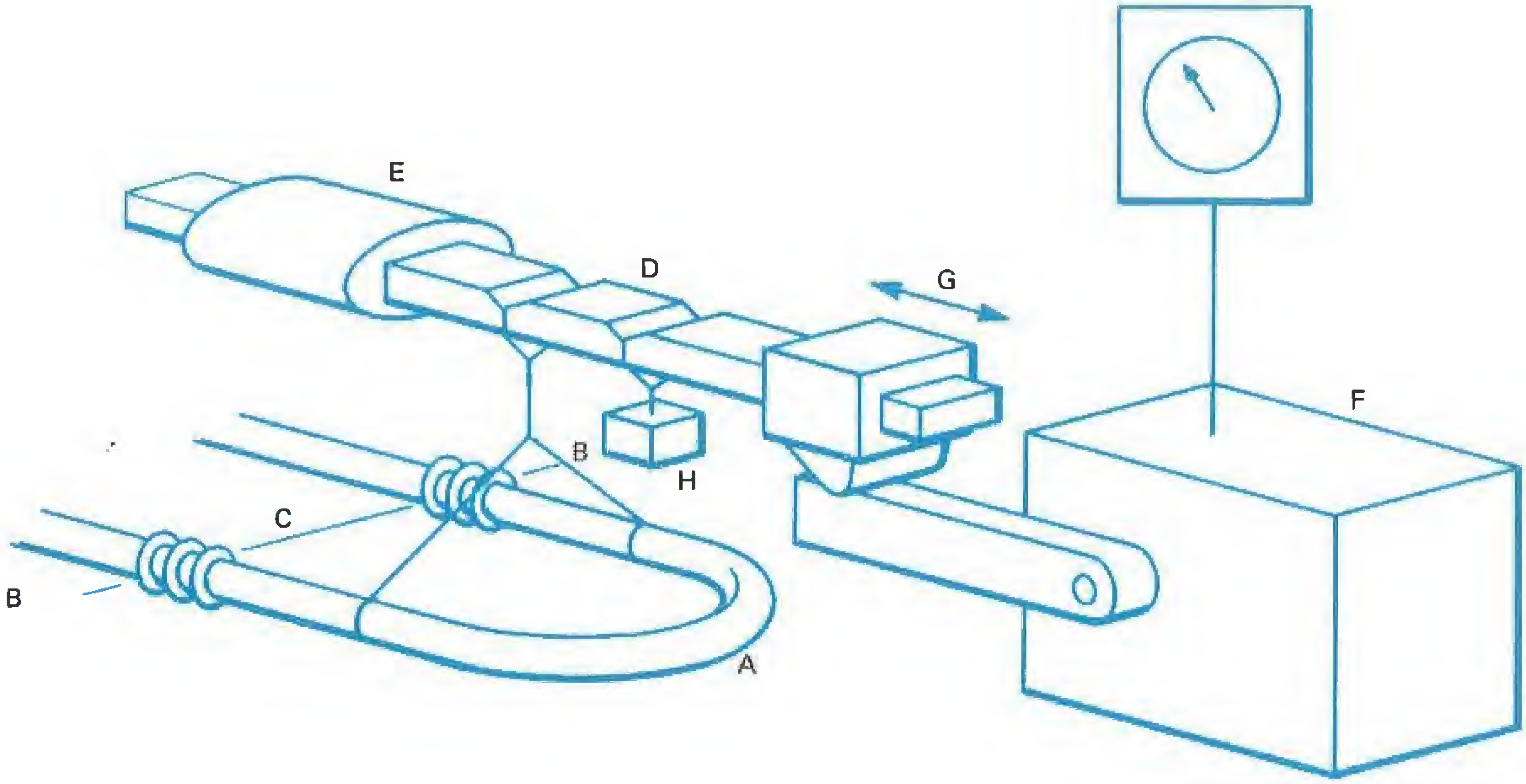


Fig. 9-6 Tube-Loop Balance Density Meter

density indications. In case of a slurry, the rate of flow must be such that deposits of solid materials do not form.

The force balance is pneumatically operated and gives an output signal which is indicated or recorded on a pneumatic receiver. Variation from this arrangement is possible in respect to the materials which are in contact with the fluid. The tube loop may be hard rubber or glass and the flexible connectors may be in the form of bellows.

An electrical force balance can also be used in place of the pneumatic system. It gives an electrical output that is proportional to the density variation. This type of meter is very sturdy in design and construction and is sensitive enough to detect density changes as small as 0.00025 g/cm^3.

A wide variety of electrical, electronic, and pneumatic density and specific-gravity meters is available. Each has its own unique features, but all are based on the same fundamental concept of measurement.

A simple method of measuring density of liquid is to use a weight measuring device such as an electrical load cell or a mechanical balance. A load cell is an electromechanical device which employs a strain-gage transducer. When the mechanical portion is deflected by a weight, the strain gage is distorted, causing a change in electrical resistance. By using and electrical bridge network, the resistance can be measured. In this way, it is possible to have a remote indication of the density. This scheme can also be used for continuous measurement where the fixed volume is enclosed in a container through which the process liquid flows.

The density of a liquid can also be measured by using a radioactive technique. A radioactive source, such as cobalt or radium, is placed on one side of the tank with its ray directed across the tank toward a radioactive

sensing cell such as a Geiger counter. The amount of energy remaining after the ray passes through the tank walls and the liquid is a function of the density of the liquid.

When a substance is heated its volume increases but its weight remains unchanged. Since density is defined as

$$\boxed{\text{Density} = \frac{\text{weight}}{\text{volume}}}$$

the density decreases when the substance is heated. An equation to be used to find the weight density of a substance at any temperature other than 0°C can be found by the following techniques:

Let V_o = volume of the substance at 0°C

V_t = volume of the substance at any temperature t°C

W = weight of substance

γ (gamma) = coefficient of volumetric expansion

and

weight density at 0°C $\frac{W}{V_o} = w_o$

weight density at t°C $\frac{W}{V_t} = w_t$

By substituting these terms into the volume-expansion equation

$$V_t = V_o\,(1 + \gamma t)$$

the result is

$$V_t = \frac{W}{w_t},\; V_o = \frac{W}{w_o} =$$

and

$$\frac{W}{w_t} = \frac{W\,(1 + \gamma t)}{w_o}$$

Hence

$$w_t = \frac{w_o}{(1 + \gamma t)}$$

Since mass density was defined as

$$p = m/v$$

it should be noted that volumetric variations will cause density changes. If the pressure is either increased or decreased, particularly in the case of gases, there will be a corresponding change in the volume in accordance with the gas law:

$$\boxed{PV = \text{constant}}$$

Some specific-gravity values for solids and liquids are given in figure 9-7. The values were determined at 39°F and atmospheric pressure.

Material	Specific Gravity
Lead	11.34
Mercury	13.546
Toolsteel	7.7 - 7.73
Oils	.88 - .94
Water	1.00
Gasoline	.70 - .75

Fig. 9-7 Specific-Gravity of Certain Liquids

MATERIALS

- 1 Hydrometer, 0.7 to 2.0
- 1 Glass tube 18-in. long Diameter must be large enough for hydrometer to fit inside
- 1 Ring stand and clamp
- 1 Cork for bottom of glass tube
- 1 Pint distilled water
- 1 Pint tap water
- 1 Pint benzene
- 1 Pint methyl alcohol
- 1 Pint acetone
- 1 Beaker
- 1 DC power supply
- 1 VOM
- 1 Precision angular potentiometer
- 1 Angle bracket 1 X 2-1/2 X 1/4 in.
- 1 One cup container with ball
- 1 Spring sufficient to hold back the liquid weight
- Supply of angle brackets, bearings, nuts and bolts as needed

PROCEDURE

1. Attach the glass tube to the ring stand. Place the cork in the bottom of the tube.
2. Fill the tube to about one inch from the top with distilled water.
3. Place the hydrometer in the tube. Read the value of the specific gravity.
4. Record the value for the particular liquid in figure 9-10.
5. Replace the liquid in its container.
6. Clean and dry the tube completely.
7. Replace the tube on the ring stand.
8. Fill the tube with tap water as you did in step two.
9. Repeat steps 3 – 7.
10. Fill the tube with benzene.
11. Rerun the experiment.
12. Rerun the experiment for methanol, acetone, and any other liquid available.
13. Set up the apparatus as shown in figure 9-8.
14. Connect the potentiometer as shown in figure 9-9.
15. With the weight of the container only on the spring, zero the voltmeter by turning the potentiometer.

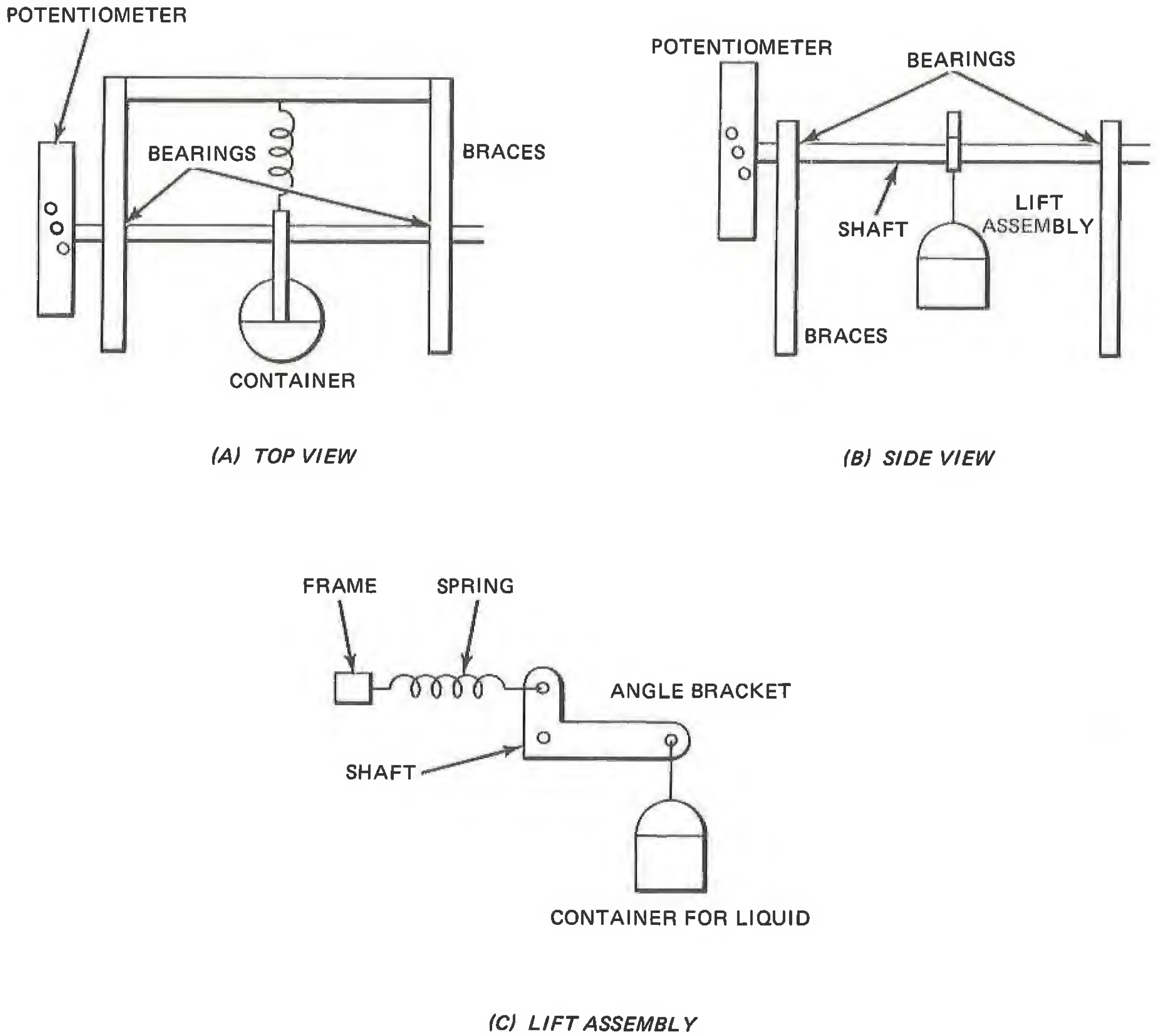


Fig. 9-8 Experimental Setup

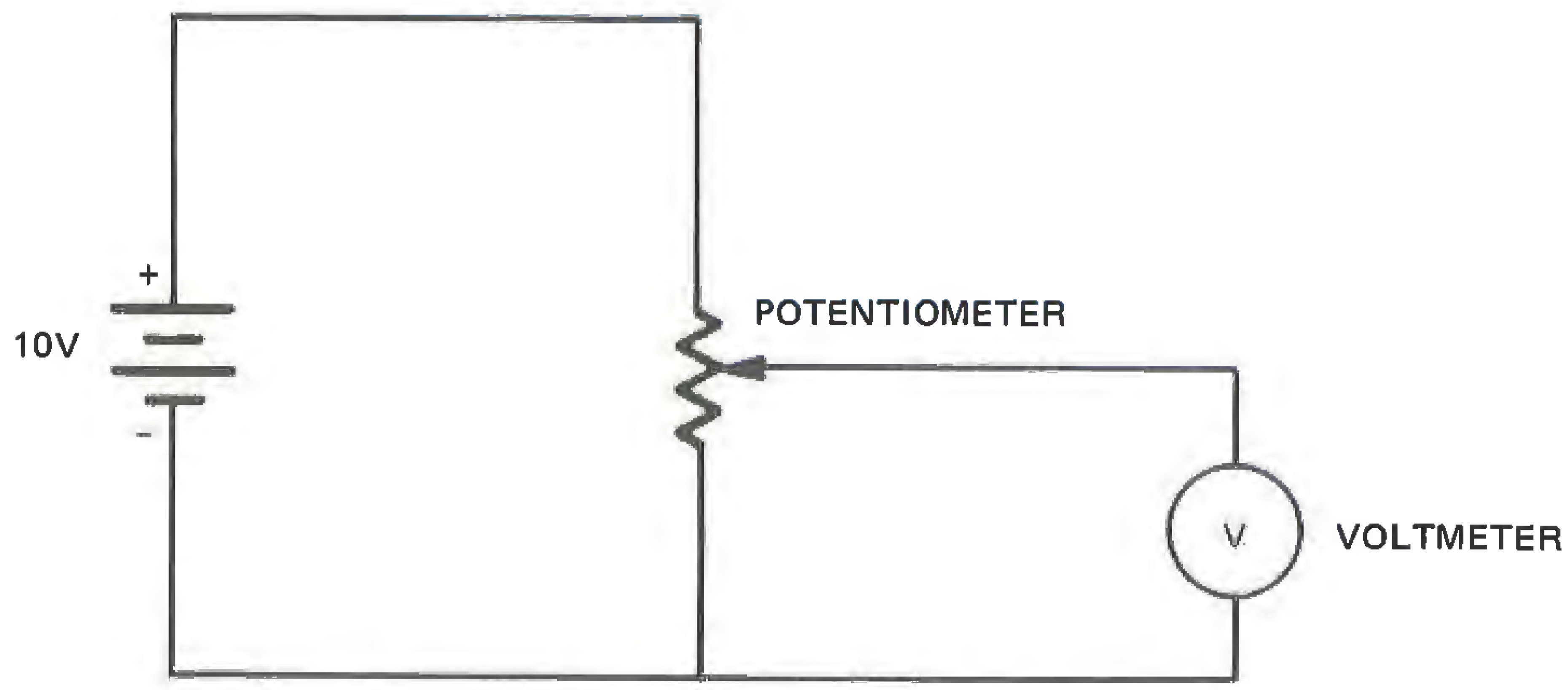


Fig. 9-9 Potentiometer Circuit

 ELECTROMECHANISMS/TRANSDUCERS

16. Remove the container and fill it with distilled water. Be sure and mark the height of the water in the container.
17. Replace the container on the stand. The spring must be strong enough to hold the container full of liquid.
18. Record the voltage across the potentiometer in figure 9-10.

Liquid	Specific Gravity	Voltage
Distilled Water		
Tap Water		
Benzene		
Methanol		
Acetone		

Fig. 9-10 Data Table of Voltage Versus Specific Gravity

19. Replace the liquid in its container.
20. Fill the container with tap water to the same level as marked in step 16.
21. Replace the container on the stand.
22. Record the voltage across the potentiometer.
23. Record the voltage across the potentiometer for each liquid used in the first part of the experiment.

ANALYSIS GUIDE. Plot a graph of specific gravity versus voltage from the data obtained. Plot voltage vertically and specific gravity horizontally. Explain how this method can be used to indicate the specific gravity of liquids in industry.

PROBLEMS

1. The specific gravity of mercury is 13.6. Find the density of mercury in grams per cm^3 and in pounds per cubic feet.
2. The weight of a substance is 870 pounds and its volume is 10.0 ft^3. What is the weight density and mass density? Assume the earth's gravity is 32.2 ft/sec^2.
3. If the weight of a cubic foot of aluminum is 167 lb at room temperature while that of water is 62.3 lb, compute the specific gravity of aluminum.

experiment 10 FLUID FLOW TRANSDUCERS

INTRODUCTION. Many industrial processes require a means for measuring fluid flow. In this experiment we will examine one method of measuring fluid flow with the use of a fluid-flow transducer.

DISCUSSION. Many different methods are used to measure flow in industrial applications. There are two aspects of this flow which can be measured: the *total quantity* of fluid flow, and the *rate* of the fluid flow.

Meters that measure the total quantity of fluid flow sometimes operate by accumulating the fluid in a chamber of known capacity and then emptying the chamber. This type of meter is used to measure water consumption in a home or company.

Another type of meter used to measure the amount of fluid flow employs a turbine wheel to drive a counter that records the total amount of fluid passing through the turbine. This meter converts the velocity of a flowing liquid to a rotary spindle motion. The fluid enters the meter and drives a turbine wheel at a speed that varies with the rate of flow. The wheel is linked to a counter through a gear train. The counter indicates the total amount of fluid flow.

There are a number of devices used to measure the rate of flow of a fluid. The simplest perhaps is the orifice plate. It consists of a disk with a hole, or orifice, of a known size through its center, placed within the pipe carrying the fluid. A pressure is built up in front of the disk as fluid moves towards it. As the fluid moves through the opening, the pressure behind the plate is reduced since a certain amount of pressure is lost overcoming the obstruction. The difference in pressure depends on the rate of flow and the size of the orifice. The greater the rate of flow, the greater the difference in pressure.

The orifice plate is usually used with some sort of differential-pressure transducer such as the manometer tube shown in figure 10-1. The greater the flow, the more difference in pressure that is indicated by the manometer. The difference is calibrated in feet per minute.

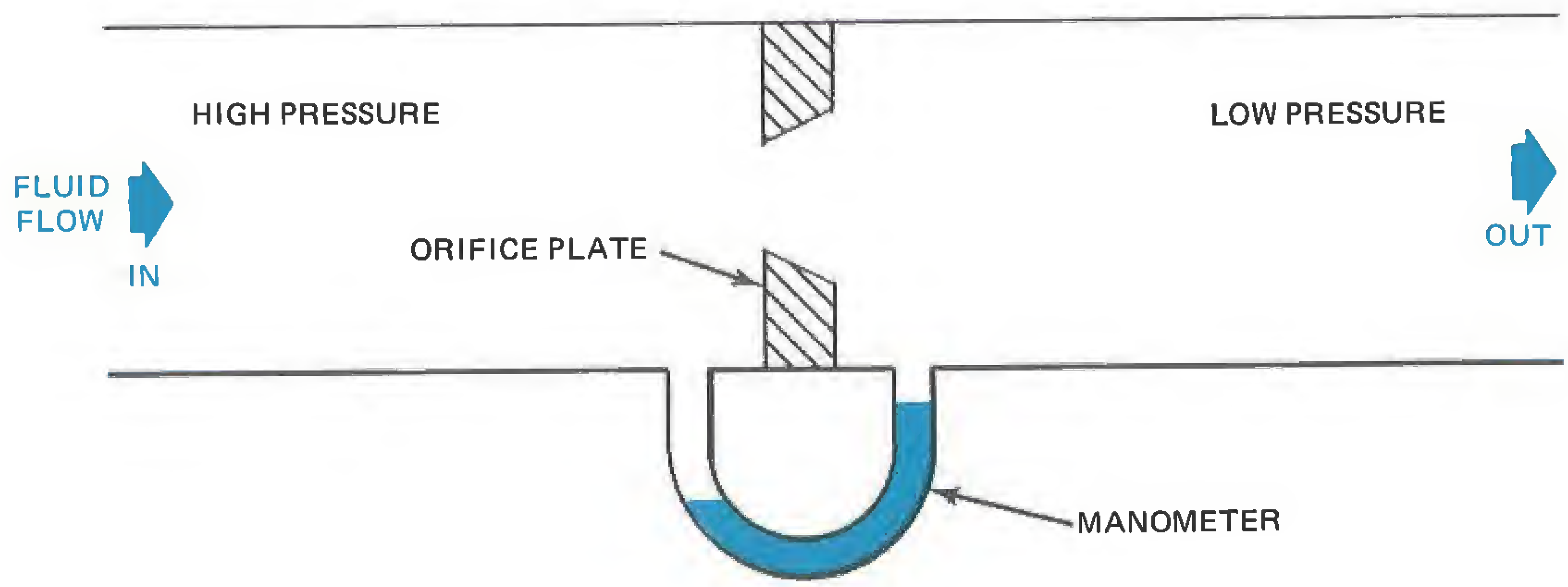


Fig. 10-1 Orifice Plate Fluid-Flow Instrument

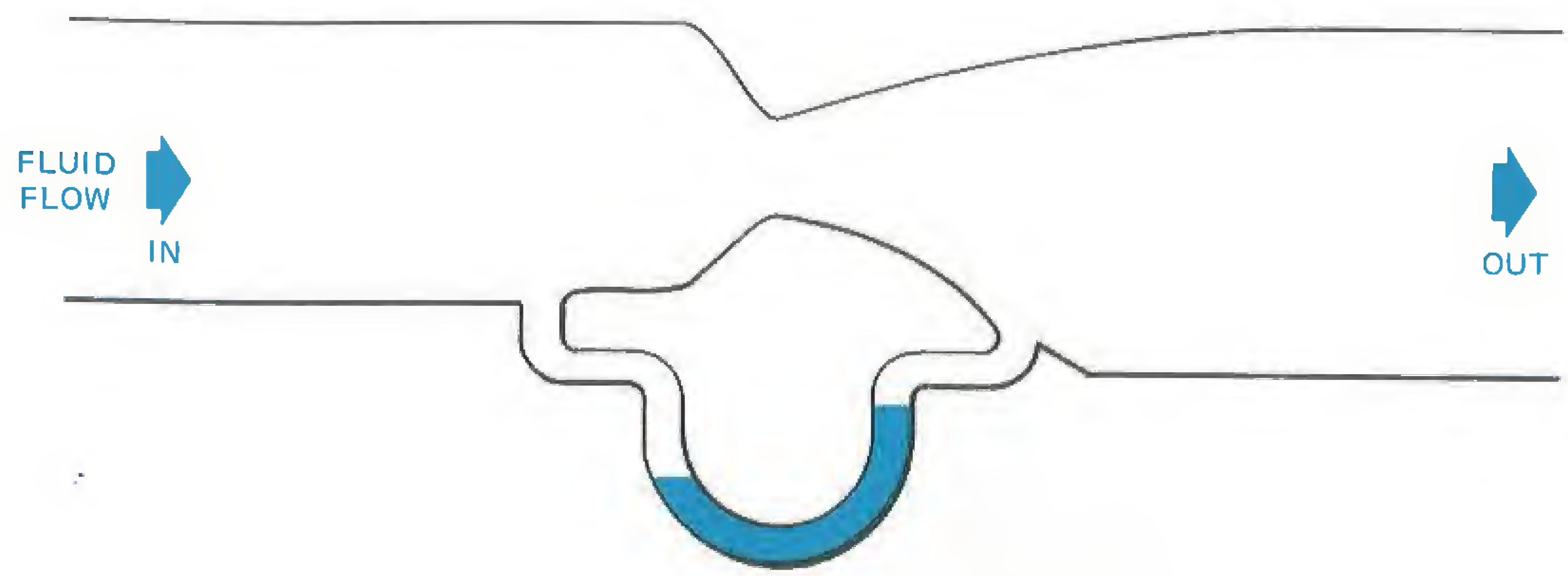


Fig. 10-2 Venturi Tube Fluid-Flow Instrument

The Venturi tube is sometimes used instead of the orifice plate. It is a specially-shaped length of pipe resembling two funnels joined at the smaller openings. This device is shown in figure 10-2.

The action of the Venturi tube is much the same as that of the orifice plate instrument, but it is more accurate. However, the Venturi tube is considerably more expensive and is much more difficult to install. The Venturi tube is usually in large pipe lines.

A compromise between the orifice plate and the Venturi tube is the flow nozzle. It is almost as accurate as the Venturi tube and it is much less expensive. This device is shown in figure 10-3.

It is important that the pressure taps be located at the correct position on the pipe to obtain the correct readings. The taps for the orifice plate are dependent upon the type of pressure measuring instrument used. For the Venturi tube, the taps should be located at the points of maximum and minimum pipe diameters to indicate maximum pressure difference. The pressure taps used with the flow nozzle are located at distances upstream from the nozzle as designated by the manufacturer. Since this location is critical, the manufacturer's recommendations must be closely followed.

There are two types of variable area meters used to indicate fluid flow. In the rotometer, the area is varied by a float in a tapered tube. Depending on the rate of flow, the float takes a position in the tube that changes the size of the area, and thus keeps the differential pressure constant. This instrument is shown in figure 10-4.

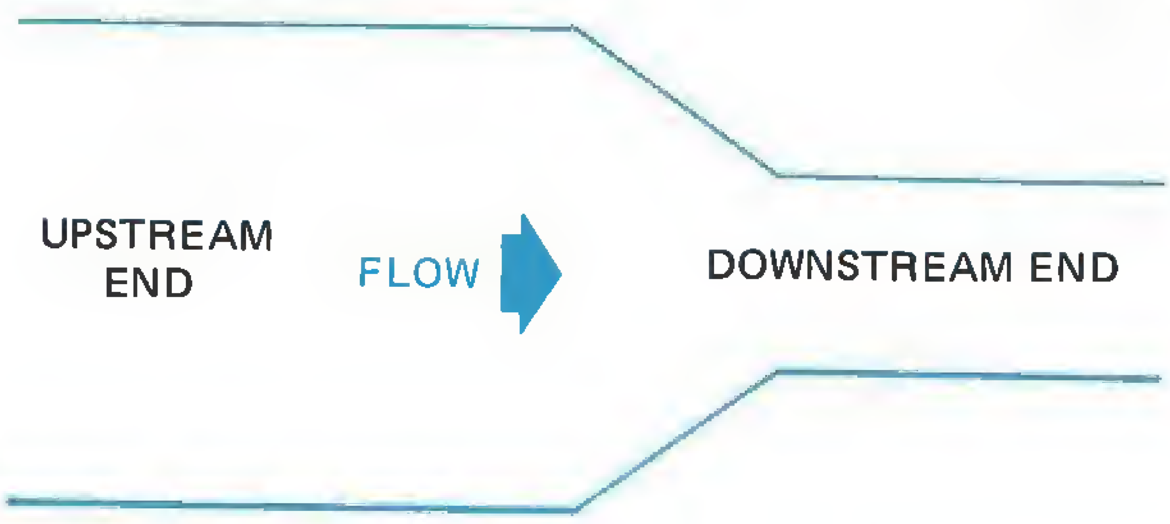


Fig. 10-3 Flow Nozzle

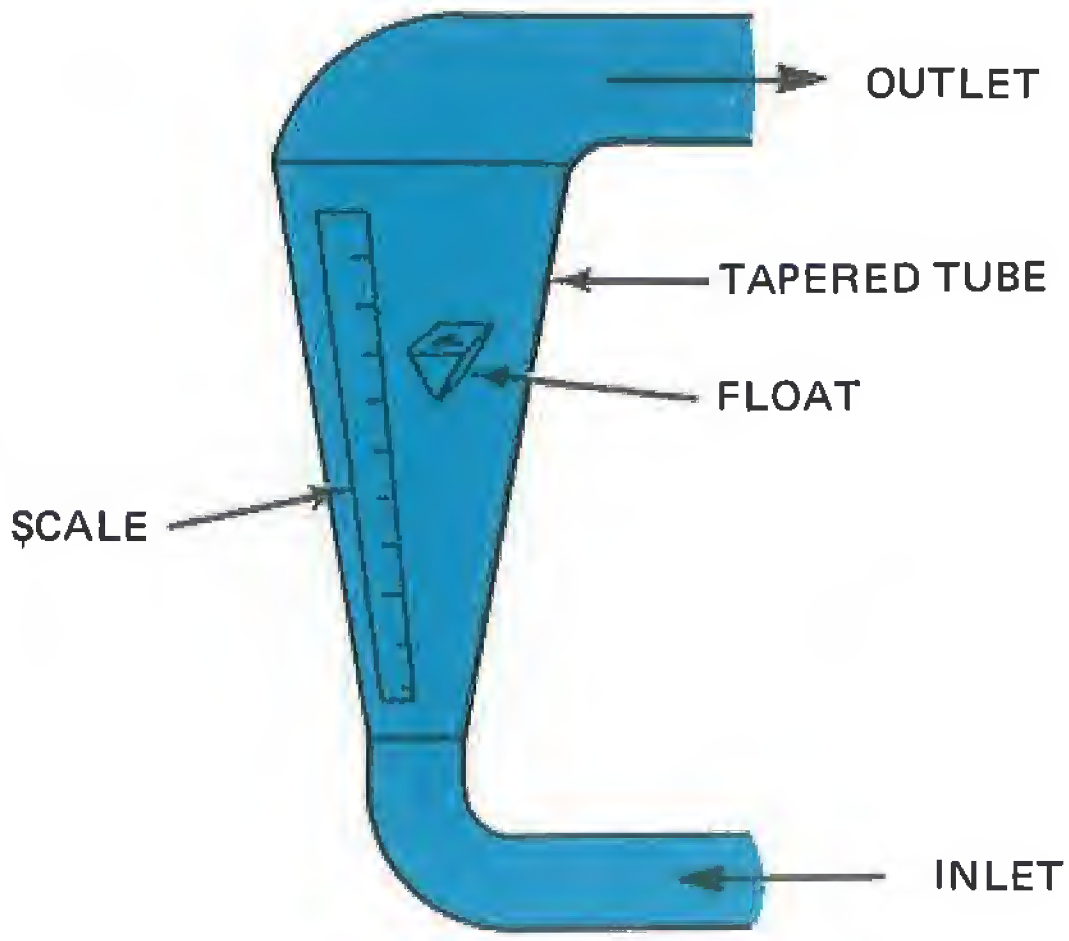


Fig. 10-4 The Rotometer

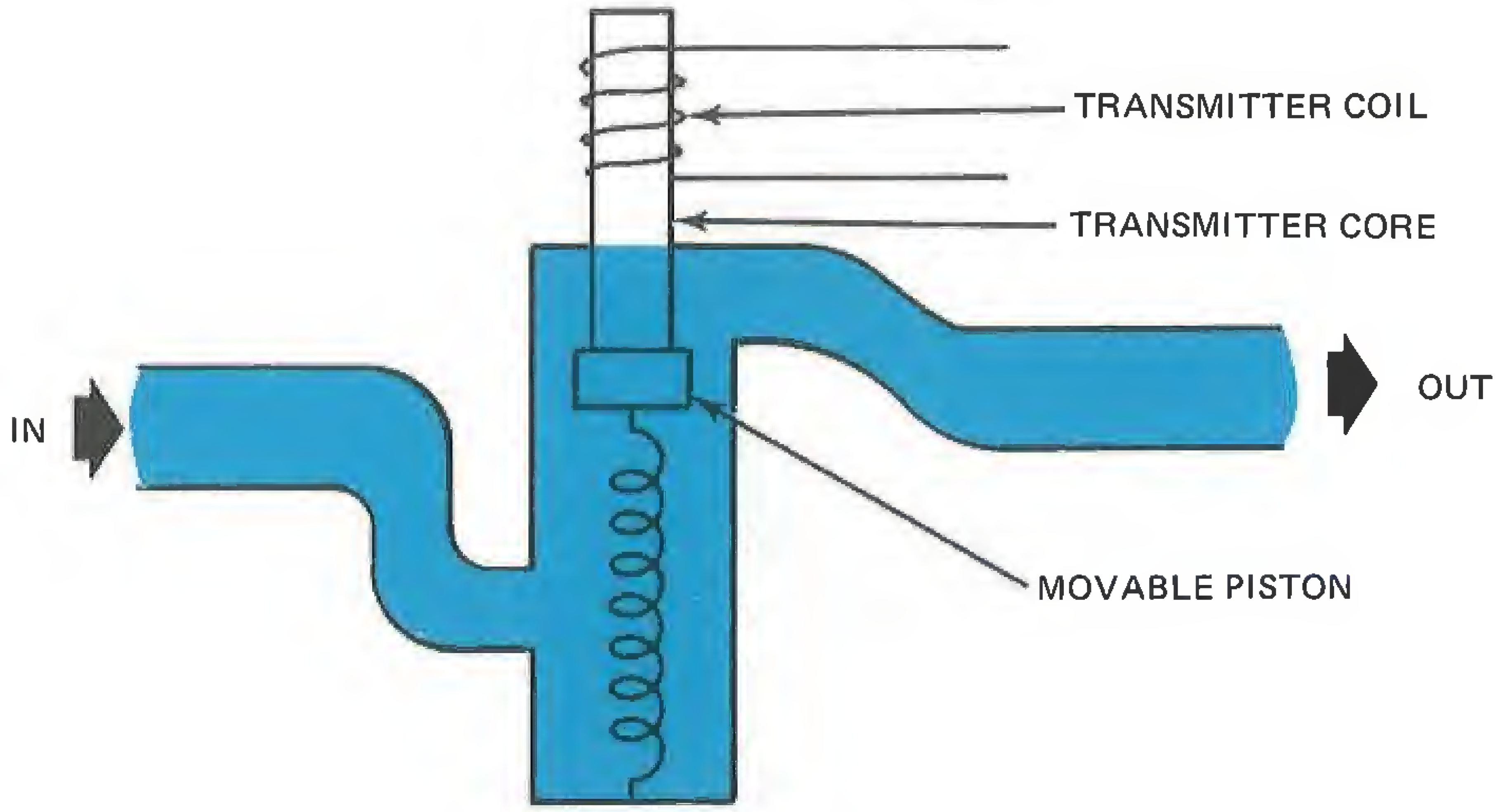


Fig. 10-5 Valve-Type Area Meter

The rotometer is chiefly used as an indicating device, although it is possible to hook the float to a follower that will vary an electrical voltage.

The valve-type area meter uses the movement of a self-positioning valve to vary the area. Like the rotometer, the valve-type meter keeps the differential pressure constant by adjusting the size of the opening area as the rate of flow changes. A specially-shaped plug or piston moves to a new position to keep the differential pressure constant for each rate of flow. The valve type meter as shown in figure 10-5 is used most often to provide remote indication.

If the adjustable piston is connected to a piece of iron which is free to move within a coil of current-carrying wire, an indication of movement can be recorded on the proper instruments. The instruments would be calibrated in gallons-per-minute or some other convenient units.

The turbine flowmeter of figure 10-6 provides a direct method for sensing the rate of flow of a fluid. As the fluid flows past

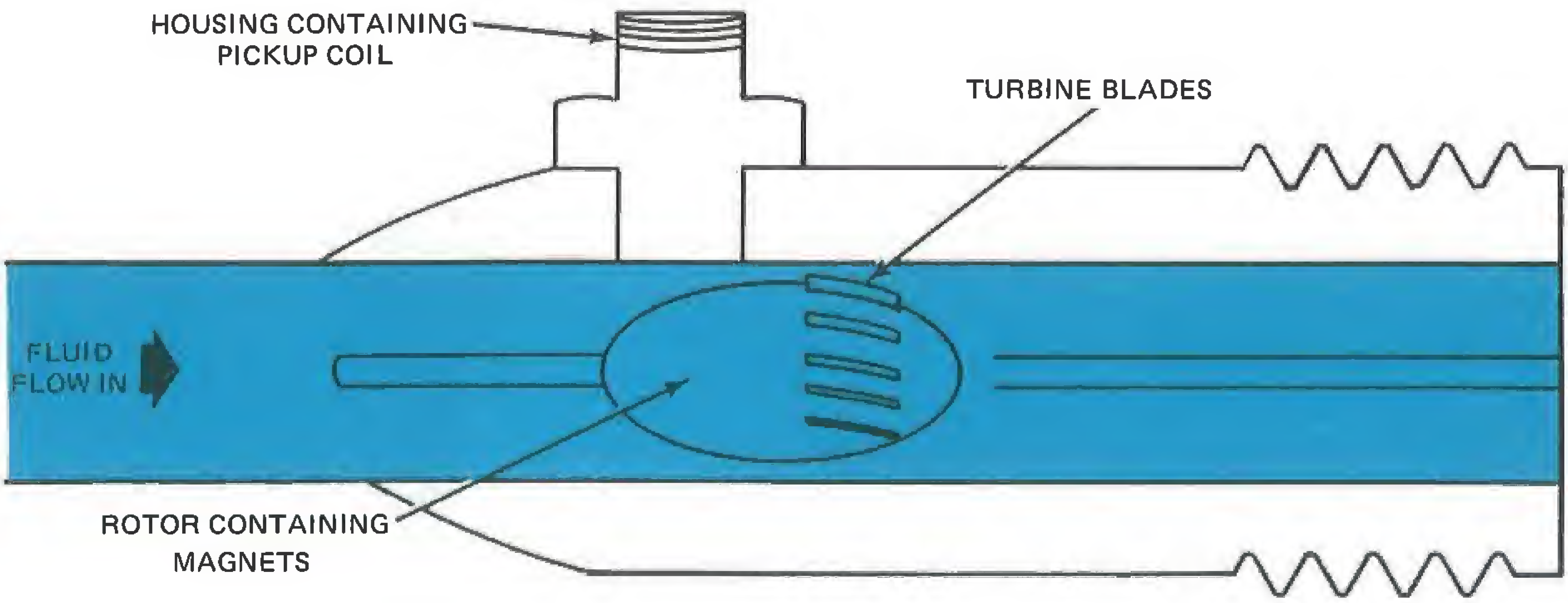


Fig. 10-6 Turbine Flowmeter

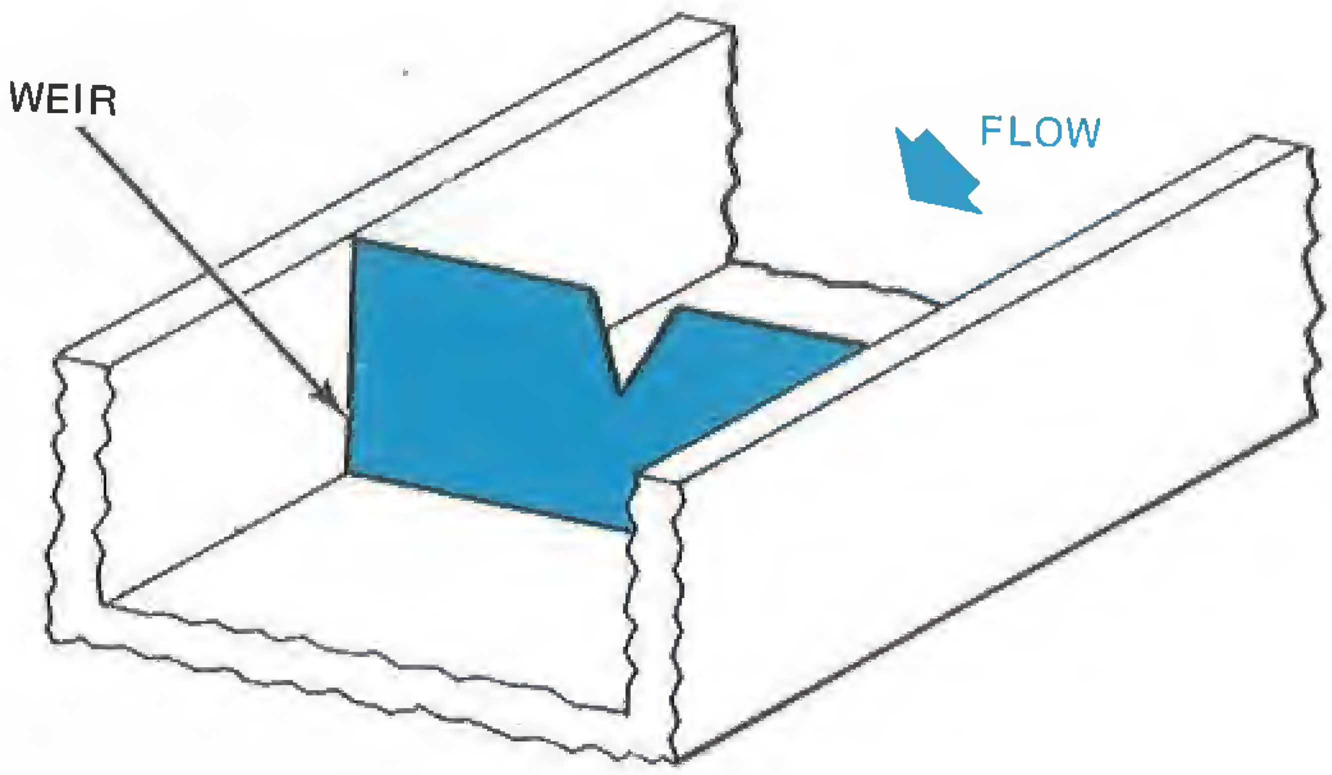


Fig. 10-7 The Weir

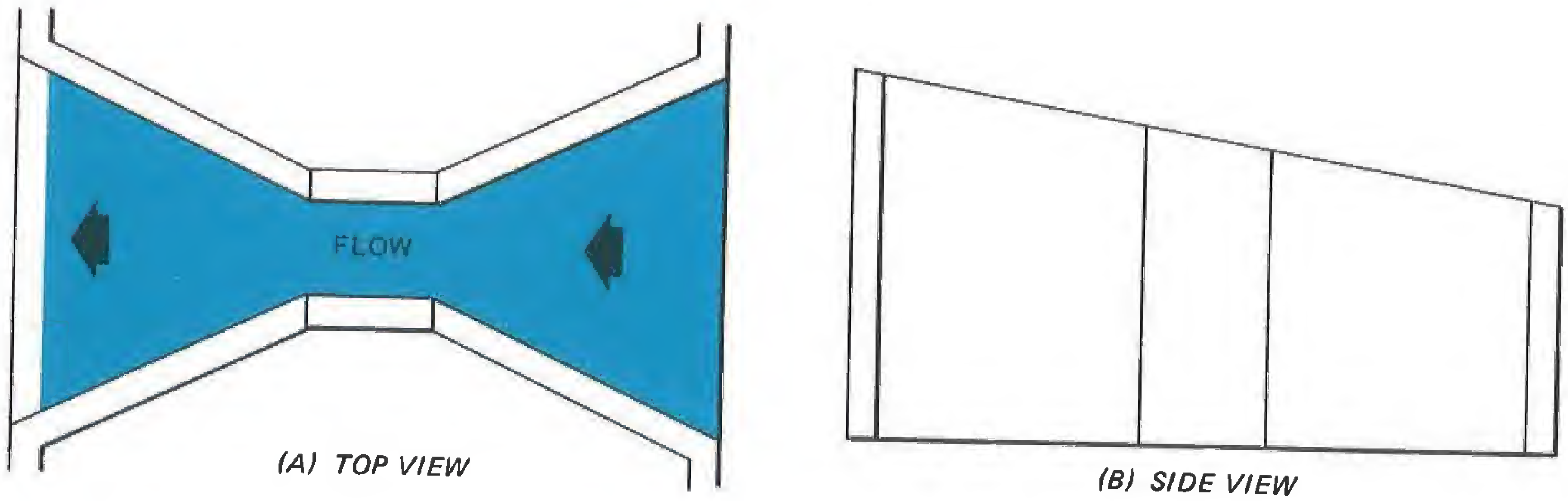


Fig. 10-8 The Flume

the set of propeller blades mounted on the rotor, they rotate. The speed of rotation is directly proportional to the rate of flow through the pipe.

The primary elements used for measuring rate of flow in open channels are weirs, flumes and open nozzles.

The weir, shown in figure 10-7, is simply a bulkhead placed across the open channel. In the flat shaped bulkhead is a specially shaped-notch. As the flow rate of the fluid-increases, the fluid is forced to rise up the notch.

A flume is another restriction-type device which is similar in appearance to the Venturi tube. It also forces the fluid to rise in a channel as the flow rate increases. A flume is shown in figure 10-8.

An open nozzle is shaped so that the level of the fluid in the nozzle rises uniformly as the flow rate increases. Such a device is shown in figure 10-9.

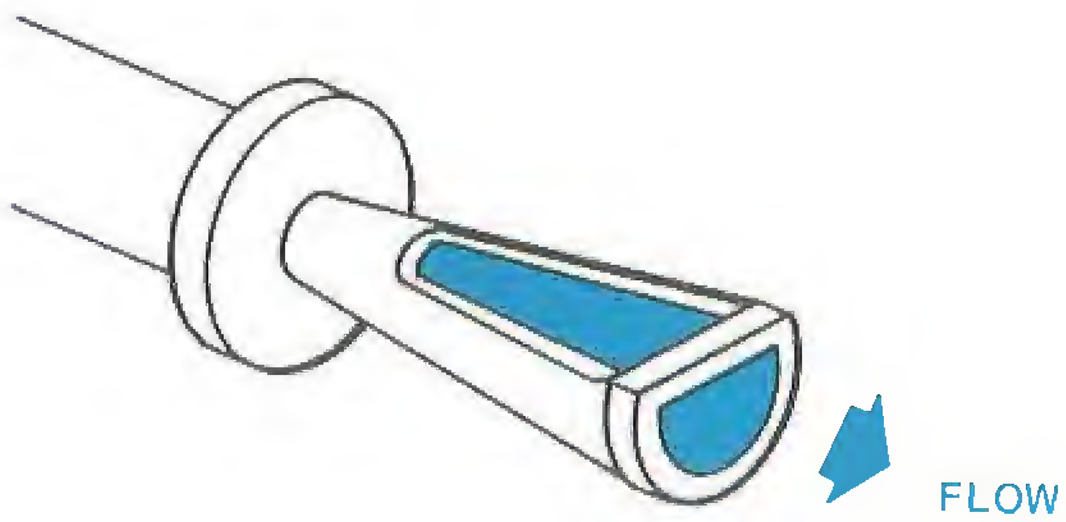


Fig. 10-9 The Open Nozzle

Weirs, flumes, and open nozzles depend upon a float-actuated device which is located in the adjoining channel to indicate the change in level due to the restriciton involved. Since the level in the channel changes with each change in flow rate, the float mechanism can be calibrated in appropriate flow rate units.

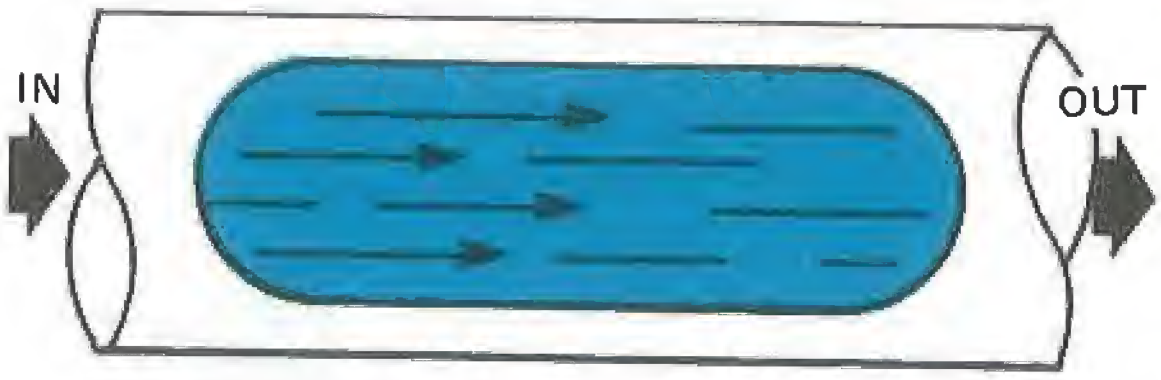


Fig. 10-10 Laminar Flow

Since the physical properties of a fluid influence its flow rate we will briefly consider some of them.

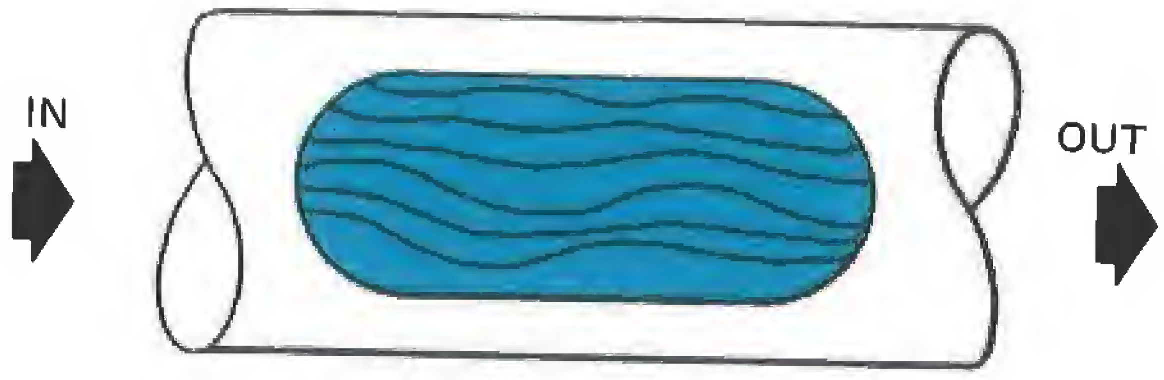


Fig. 10-11 Turbulent Flow

The pressure on the fluid is defined as the force pushing against each square inch of the fluid, or as the force the fluid exerts against each square inch of its container. Pressure is expressed in pounds per square inch.

The weight density of a fluid is defined as the weight of the fluid divided by the total volume of fluid and is expressed in pounds per cubic foot.

The viscosity of a fluid refers to its resistance to flow. There are several viscosity units, the most widely used being the centipoise. The viscosity of a liquid decreases as its temperature rises, and that of a gas increases with temperature.

The velocity of a fluid is its speed in the direction of flow. The velocity, or rate of flow, determines the behavior of the fluid. When the average velocity is relatively slow, the flow is usually laminar, as shown in figure 10-10.

When fluid has laminar flow, it flows in layers with the fastest moving layer at the center and the slower moving layers at the outer edges. As the flow rate increases, the flow may become turbulent and the layers tend to disappear. The average velocity of a fluid can be defined as

$$\text{Average velocity} = \frac{\text{rate of flow ft/sec}}{\text{area of pipe sq. ft.}}$$

In fluid flow-rate measurements, the nature of the flow is described by its Reynolds Number, which is given by

$$R = \frac{VD\rho}{\mu}$$

where
V = average velocity
D = inside diameter of pipe
ρ = fluid density
μ = viscosity

The Reynolds Number is used to determine whether the flow is laminar or turbulent. A Reynolds Number less than 2000 represents a laminar flow. If the number is greater than 4000, the flow is turbulent. Between these two numbers, the nature of the flow is unpredictable.

MATERIALS

1 Hydraulic motor
1 DC generator, approximately 3.8 volts/100 RPM
1 Hydraulic pump
1 Coupling
1 VOM
1 Stroboscope
1 Gallon container
1 Pressure relief valve
1 Watch with a second hand (supplied by student)
Hydraulic hoses and couplings as needed

PROCEDURE

1. Connect the hydraulic circuit as shown in figure 10-12.

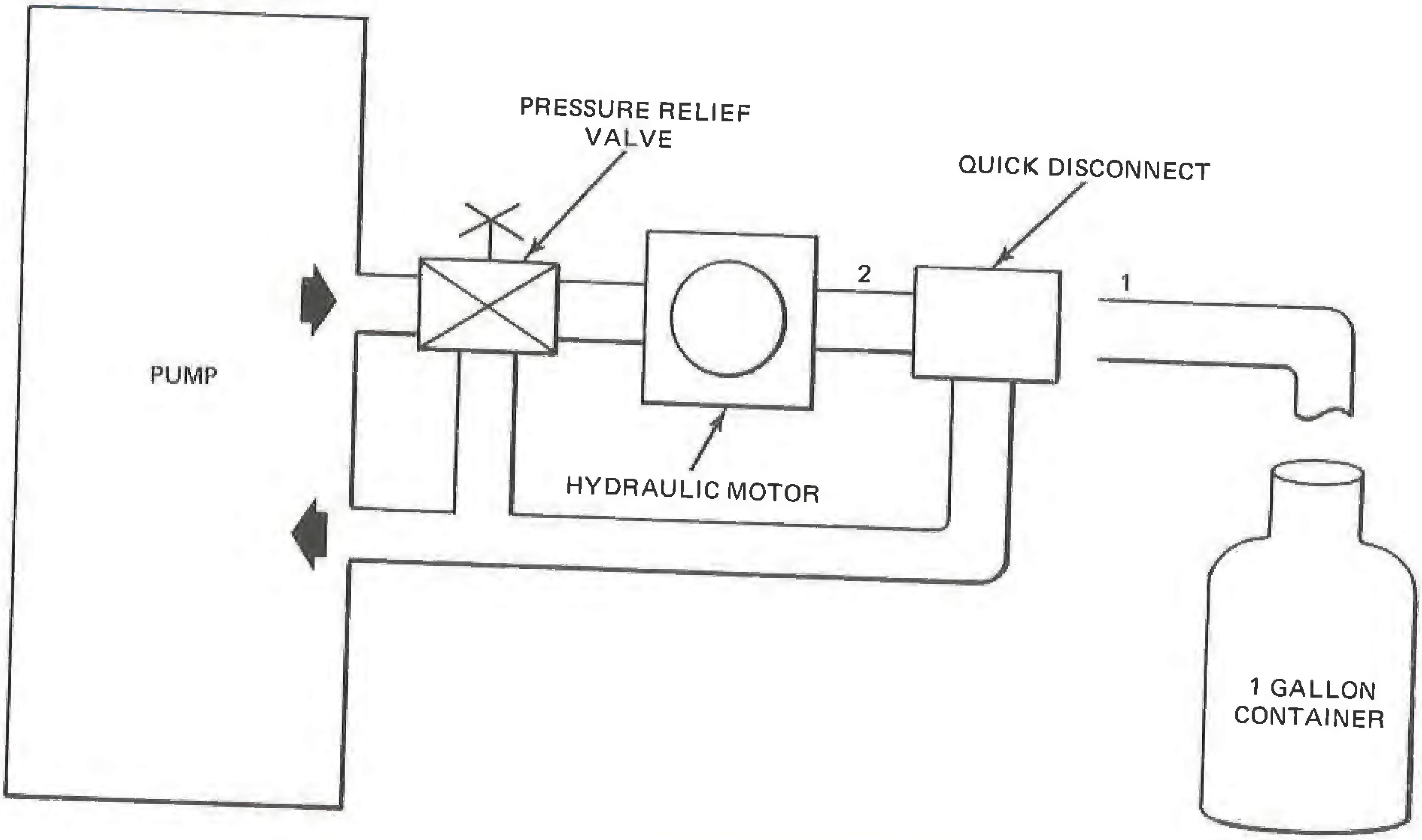


Fig. 10-12 Experimental Setup I

2. With the pump running, increase the pressure with the relief valve until the hydraulic motor is running at 700 RPM. Measure the speed with the stroboscope.
3. Turn the pump off and disconnect hose two.
4. Connect one end of hose one to the output of the motor. Place the other end in the one gallon container.
5. With the relief valve at the same setting, turn the pump on and fill the container. Measure the time it takes to collect one gallon of fluid.
6. Record this time in the data table, figure 10-14.
7. Return the fluid to the pump reservoir.

8. Disconnect hose one and reconnect hose two.
9. Turn the motor on and increase the pressure with the relief valve until the hydraulic motor speed is 1000 RPM.
10. Repeat steps 3, 4, 5, 6 and 7 for this speed.
11. Repeat this part of the experiment for 1500 RPM.
12. Change the experimental setup to the one shown in figure 10-13.

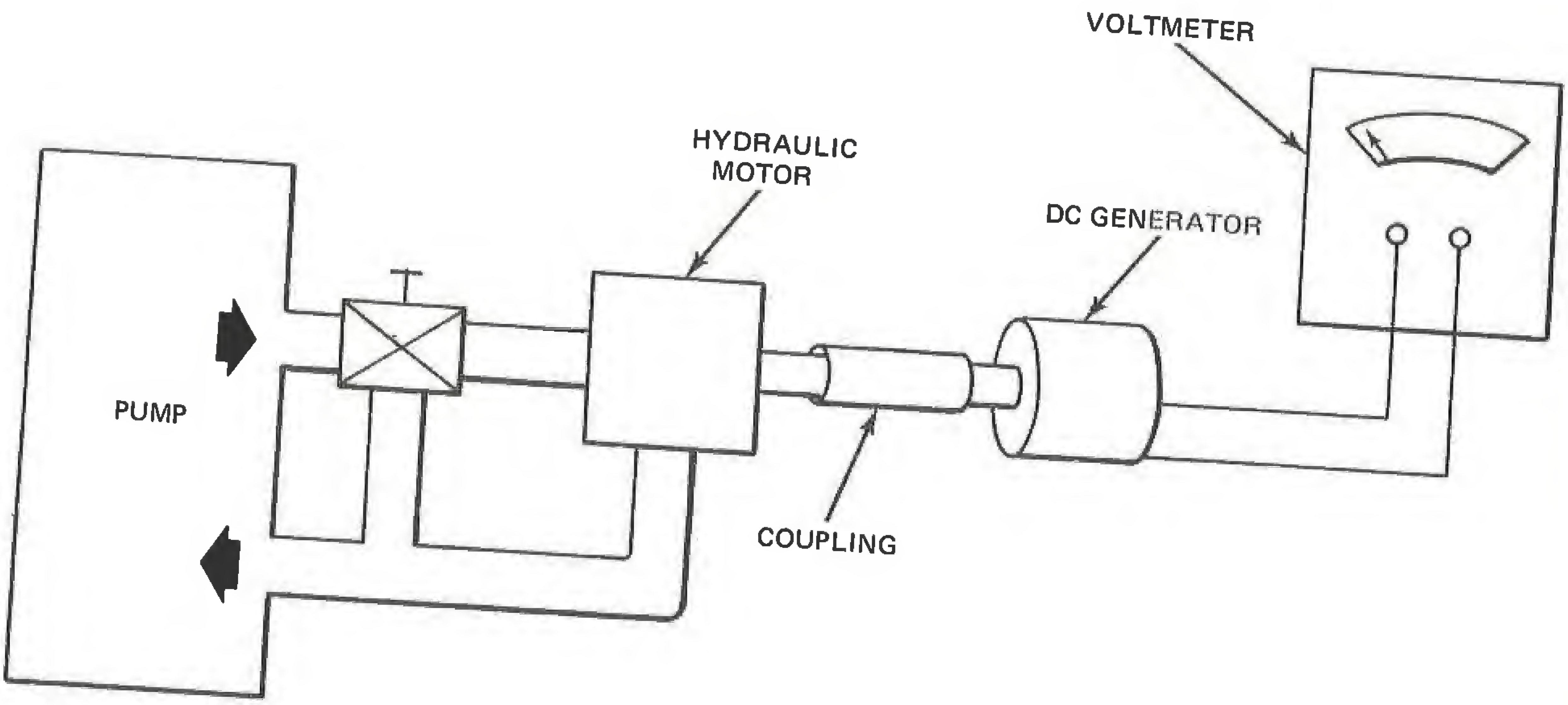


Fig. 10-13 Experimental Setup II

13. With the pump running, set the relief valve until the hydraulic motor is running at 500 RPM.
14. Record the voltage output of the generator in the data table, figure 10-15.
15. Increase the pressure until the motor speed is 1000 RPM.
16. Record the output voltage of the generator.
17. Repeat the experiment for 1500 and 2000 RPM.
18. Record the voltage outputs.
19. For each RPM used in figure 10-14, multiply the number of RPMs times the time in minutes divided by the number of gallons collected. This will give the revolutions per gallon of the hydraulic motor.
20. Find the average revolution per gallon.
21. Divide the RPMs in figure 10-15 by the average number of revolutions per gallon. This will give the flow rate of the line at the particular RPM of the hydraulic motor.

Amount of Fluid	RPM	Time	Rev./Gal
1 Gallon	700		
1 Gallon	1000		
1 Gallon	1500		
Average Rev./Gal.			

Fig. 10-14 Data Table for Revolutions per Gallon

RPM	Voltage Output	Gal./Min.
500		
1000		
1500		
2000		

Fig. 10-15 Data Table of Flow Rate Versus Voltage Output of Generator

ANALYSIS GUIDE. Plot a graph of voltage output versus flow rate of the hydraulic line. How could this set-up be adapted to be used in an oil field pumping station to measure the flow rate of the oil in various pipe lines? How can the graph be used if different voltage outputs were recorded?

PROBLEMS

1. What are the two flow measurements and what is the difference between them?
2. Why is a rotometer called a variable-area flow meter?
3. Identify the physical properties that affect fluid flow.
4. Describe the difference between laminar and turbulent flow.

experiment 11 LIQUID LEVEL TRANSDUCERS

INTRODUCTION. The control of liquid levels is necessary in many industrial processes. In this experiment we will investigate the operation of a liquid level transducer.

DISCUSSION. The vast quantity of water used in industry, not to mention the solvents, chemicals, and other liquids which are used in processing materials and products, makes liquid-level measurement and control essential in industrial manufacturing plants. Instruments for the measurement of liquid level in various containers are classified as follows:

Mechanical — direct and indirect
Pneumatic
Electrical
Nucleonic
Ultrasonic

The liquid-level range, the nature of the liquid, the operating pressures and the cost involved are factors which determine the type of instrument or gage that is used.

Perhaps the simplest and most inexpensive liquid-level measuring device is the dipstick. This is an example of a direct method of measuring and is used for measuring the oil level in an automobile, or the height of fuel in a gasoline storage tank. However, this method does not adapt itself to continuous measurement such as that required in an automobile for measuring the fuel level.

Another direct measuring device is a sight-glass which is mounted on the outside of a tank as shown in figure 11-1. As the level of the liquid in the tube rises and falls in the tank, the level of the liquid in the sight glass moves up and down, maintaining the same level as that of the liquid in the tank. In some tanks where the temperature is very high, a correction may have to be made because of the density variation. The temperature of the liquid in the glass tube will be lower than that in the tank, causing a difference in density which will affect the actual level reading.

A float is an inexpensive level-measuring device which utilizes Archimedes' principle to measure liquid-level directly and continuously. Archimedes observed that a floating body is buoyed up by a force equal to the weight of the liquid it displaces. The primary element is a float which, because of its buoyancy, will follow the varying liquid level. A transducer or converting device can relay the float travel to a pointer or pen arm of a recorder.

Such a device might resemble the one shown in figure 11-2. It consists of a float, a counterweight, and a flexible connection

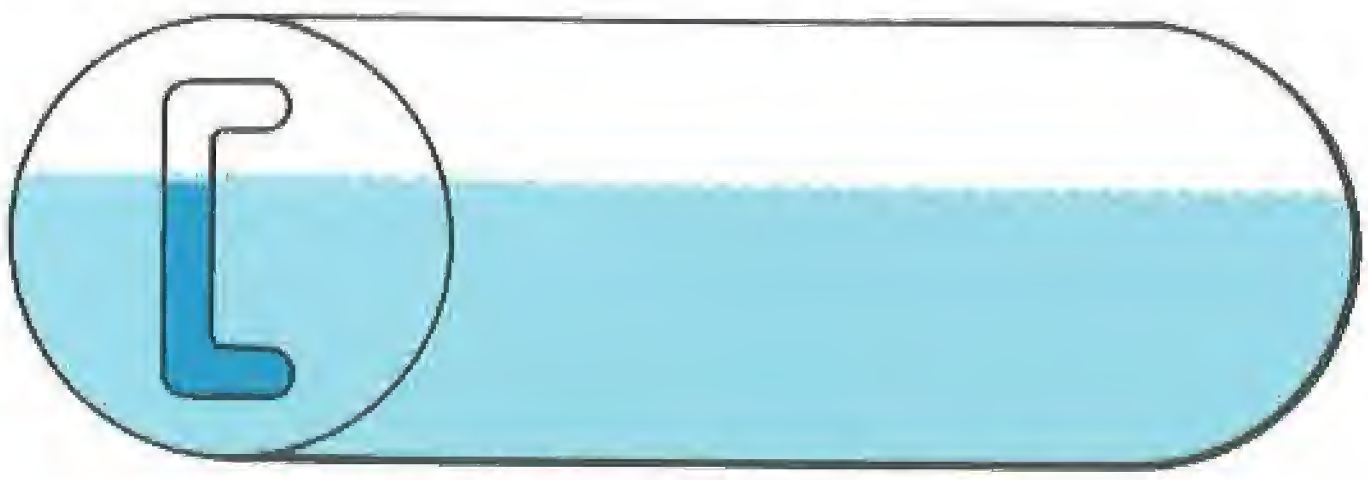


Fig. 11-1 Sight Glass on the End of a Tank

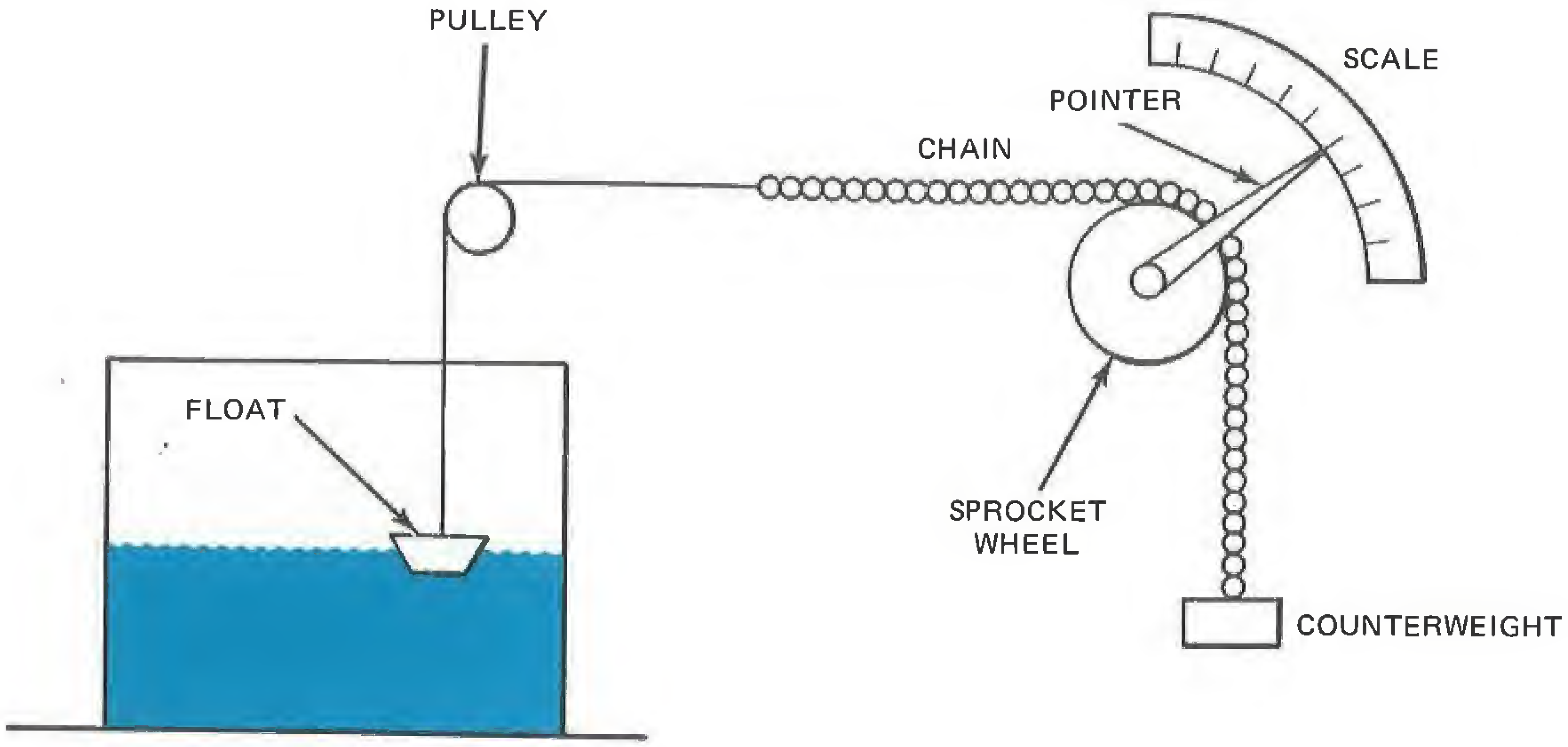


Fig. 11-2 Float Level Gage

which can be a chain or thin metallic tape. The counterweight keeps the chain under tension and takes up slack as the level moves up and down. The scale continuously indicates the level of the liquid because any movement of the sprocket wheel will move the pointer.

Another type of float-operated instrument has the float attached to the shaft directly as shown in figure 11-3. The motion of the float travel on the surface of the liquid is transferred to the shaft and the level is indicated on a scale.

In a liquid of a given specific gravity, the weight displacement remains constant regardless of the level position. The float rises and falls the same distance as the actual liquid level, and the position of the float is a direct indication of level.

The fuel-level gage found in the automobile makes use of a float which is mechani-

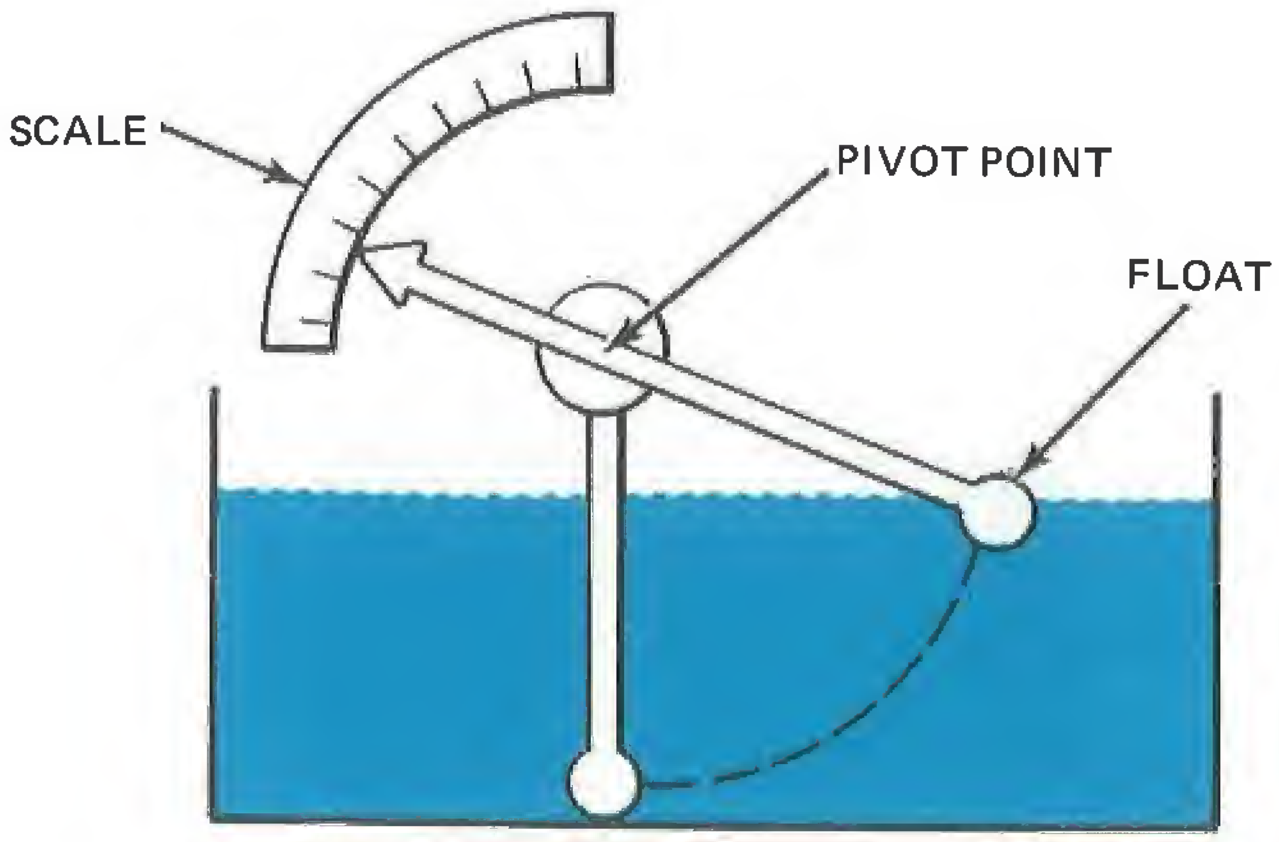


Fig. 11-3 Rotating Shaft Level Gage

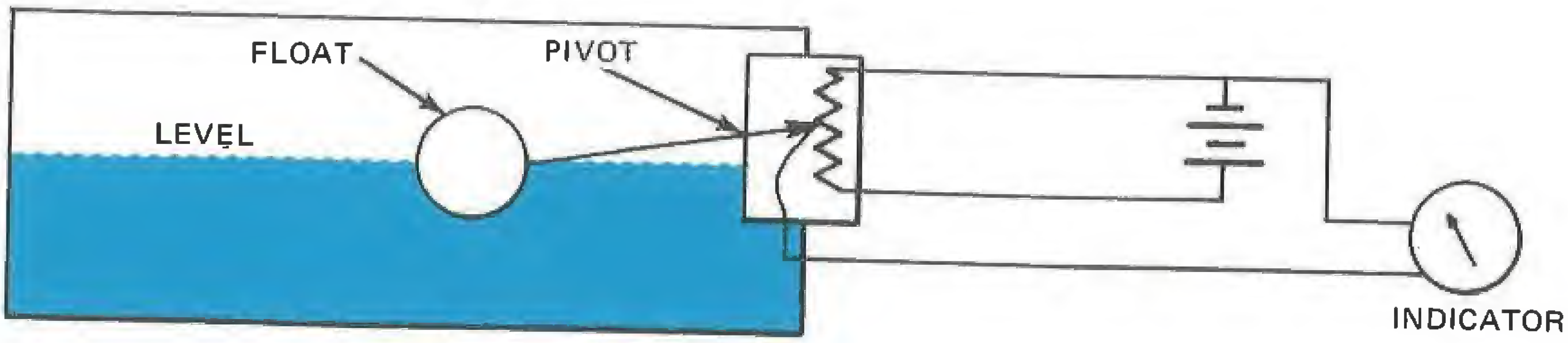


Fig. 11-4 Fuel-Level Indicator for an Automobile

cally linked to a potentiometer. The output voltage across the wiper and the common ground is recorded on an appropriate meter on the dash panel. A simplified schematic of such a device is shown in figure 11-4.

The variable-displacement gage shown in figure 11-5 uses Archimedes' principle to move a level arm balance. The more the displacer is submerged, the greater is the force created by the submerged body. Although the displacer rises and falls with level changes, the movement is very much less than the actual level variation.

For indirect measurement, there are several types of level measuring devices that are operated by pressure. The simplest method is to put a pressure gage at the bottom of a liquid vessel. Any rise in the level causes an increase of pressure. The gage scale is marked in units of level measurement (feet or inches).

If the liquid is such that it will damage the pressure gage, an air pocket can be used with a diaphragm to transmit the pressure.

The diaphragm box is connected to the container. The diaphragm transmits air pressure to the gage. As the level of the liquid rises, the pressure on the diaphragm increases. The corresponding reading is given on the pressure gage.

One type of electrical level gage makes use of two electrodes separated by an insulating fluid. This type of level gage is known as the capacitive type. It is suitable only for liquids which are dielectrics.

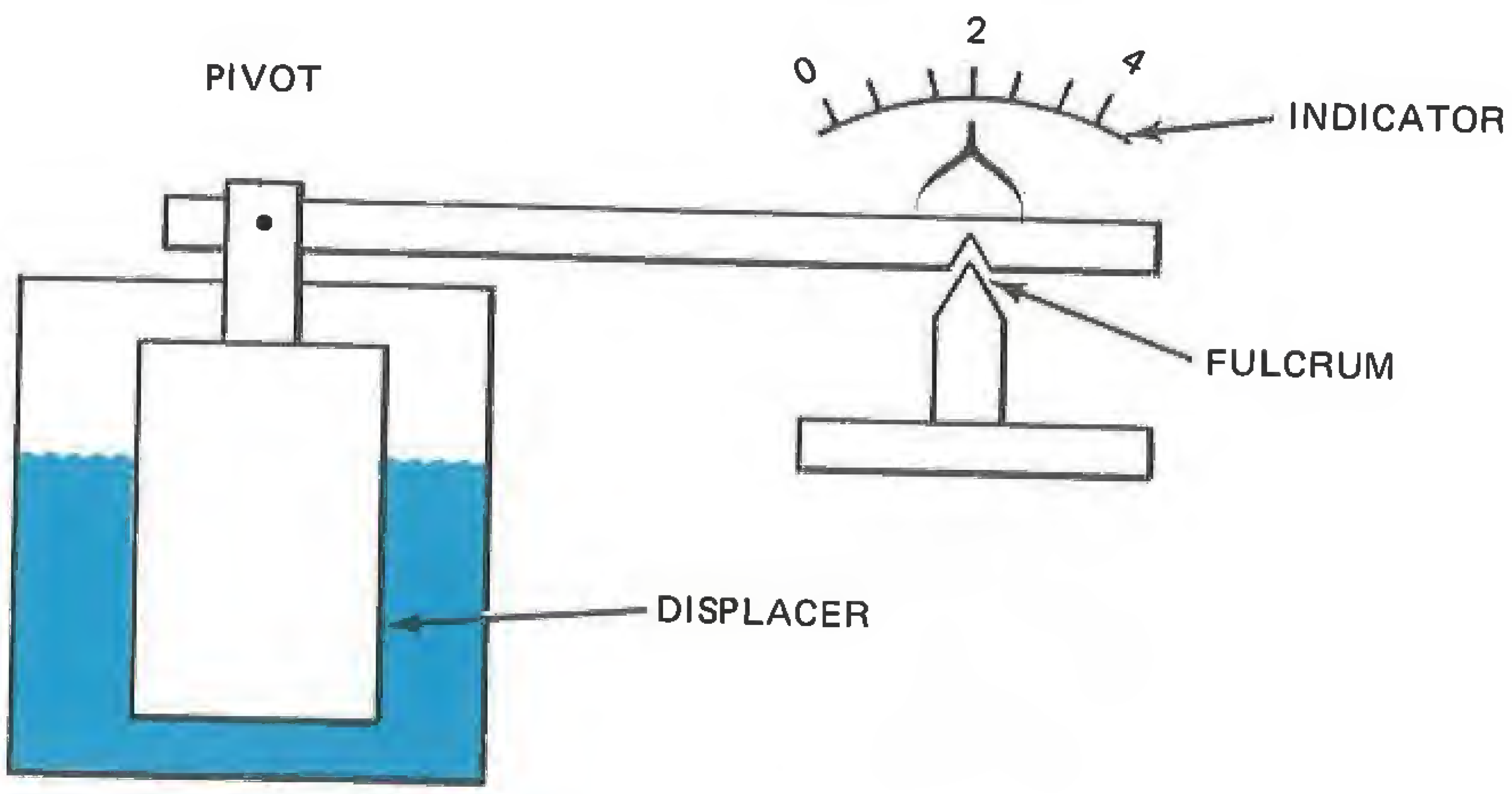


Fig. 11-5 Displacer Type Level Indicator

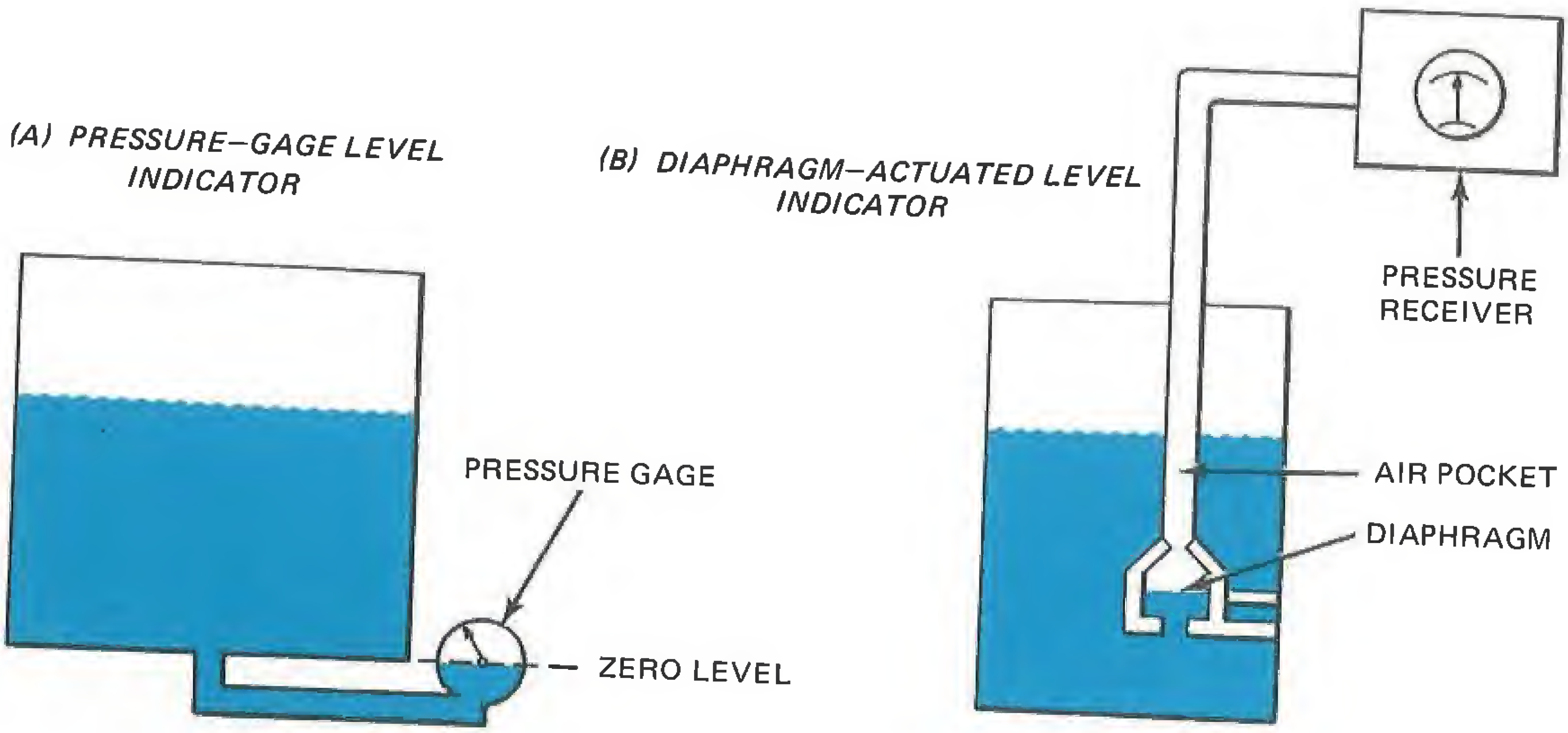


Fig. 11-6 Pressure-Type Level Indicators

When an electric potential is applied across the capacitor plates, there will be a removal of electrons from one plate and an addition of the same number of electrons to the other plate. The passage of electrons depends upon the space between the plates, the area of the plates, the nature of the dielectric between the plates and the voltage applied. The equation used to find the capacitance is

$$\boxed{C = \frac{2.3 \times 10^{-1} \times KA}{S}} \qquad (11.1)$$

where

C = capacitance in $\mu\mu$F (10^{-12} Farads)
A = area of the plates, in^2
S = space between the plates, inches
K = dielectric constant

Capacitance varies directly with liquid level and, therefore, can be used for liquid level measurement and control purposes. Such a system is shown in figure 11-7. The capacitance will be at a minimum when the tubes contain only air and at a maximum

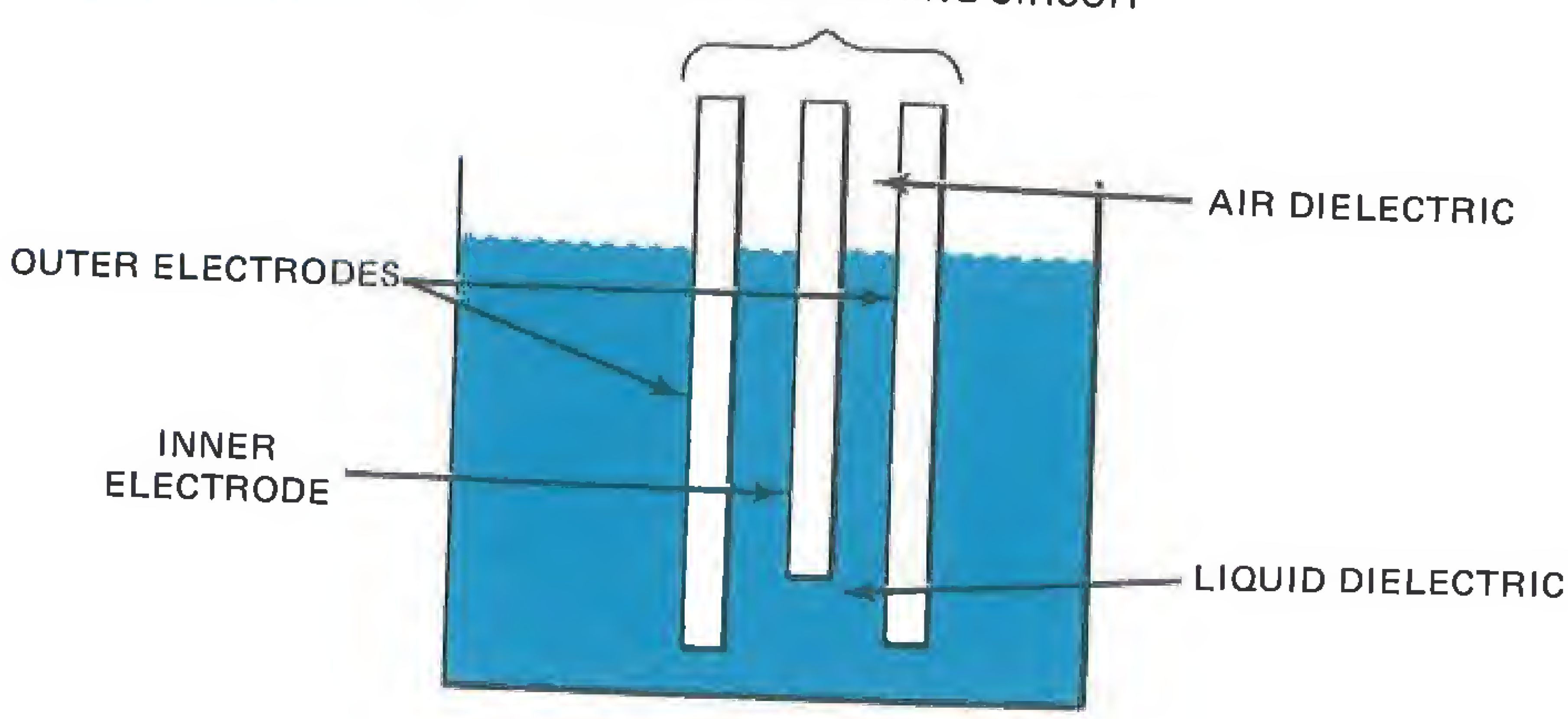


Fig. 11-7 Capacitance-Type Level Gage

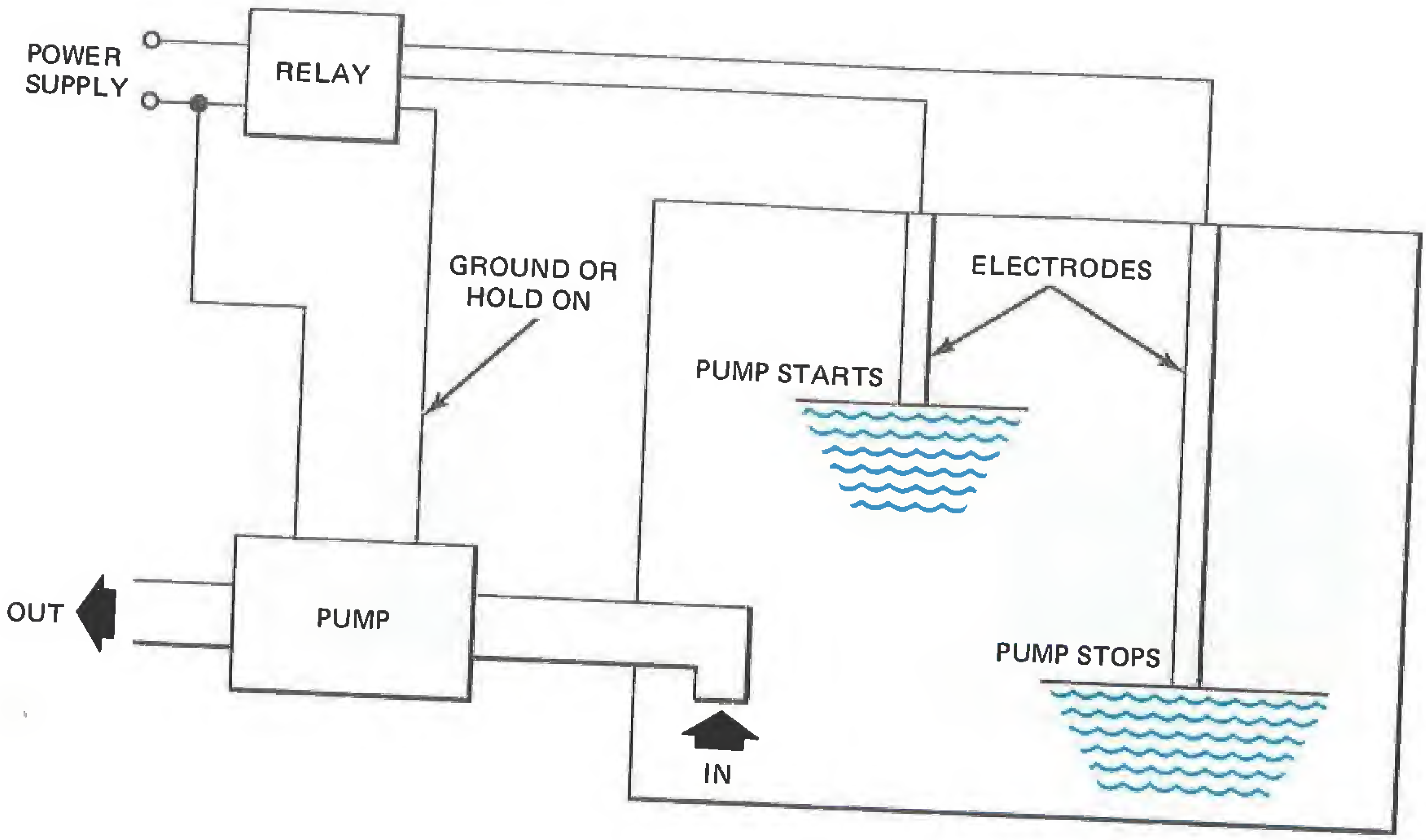


Fig. 11-8 Drainage-Control System

when the liquid fills the entire space between the electrodes. The liquid level can be measured by obtaining a balance in one arm of a Wheatstone bridge. The output of the bridge may be amplified and fed to a servomotor which will rebalance the bridge automatically and thus indicate the level reading.

The range of the capacitance level-measuring gage is from a few inches to several hundred feet. The material used for the electrodes will vary according to the applications. For corrosive liquids, stainless steel is normally used while for other liquids, most common metals are satisfactory.

This system will also work with solid materials. The storage tank acts as the dielectric. The other electrode is an insulated wire positioned vertically in the center of the tank or container.

Another type of electrical level control is used when the liquid is a conducting material. The equipment used is shown in figure 11-8. The electrodes are of different lengths, the lengths being adjusted to correspond with two levels between which the pump will operate. The relay is connected to the electrodes. When the liquid rises to the top electrode, it completes the circuit which activates the relay. The relay then starts the motor on the pump which pumps liquid out of the tank. The ground or hold-on wire will keep the pump running until the level falls below the bottom electrode which will shut off the pump. Restarting commences only when the level reaches the upper electrode.

Level gages which operate with the use of a radioactive material are sometimes used in industry. Such devices consist of a radioactive source, a radiation detector and an electrical measuring circuit incorporating an amplifier and readout instrument. Nuclear gages cover a wide range of applications. Installations will operate on high- and low-level alarms for storage tanks as large as 50 feet in

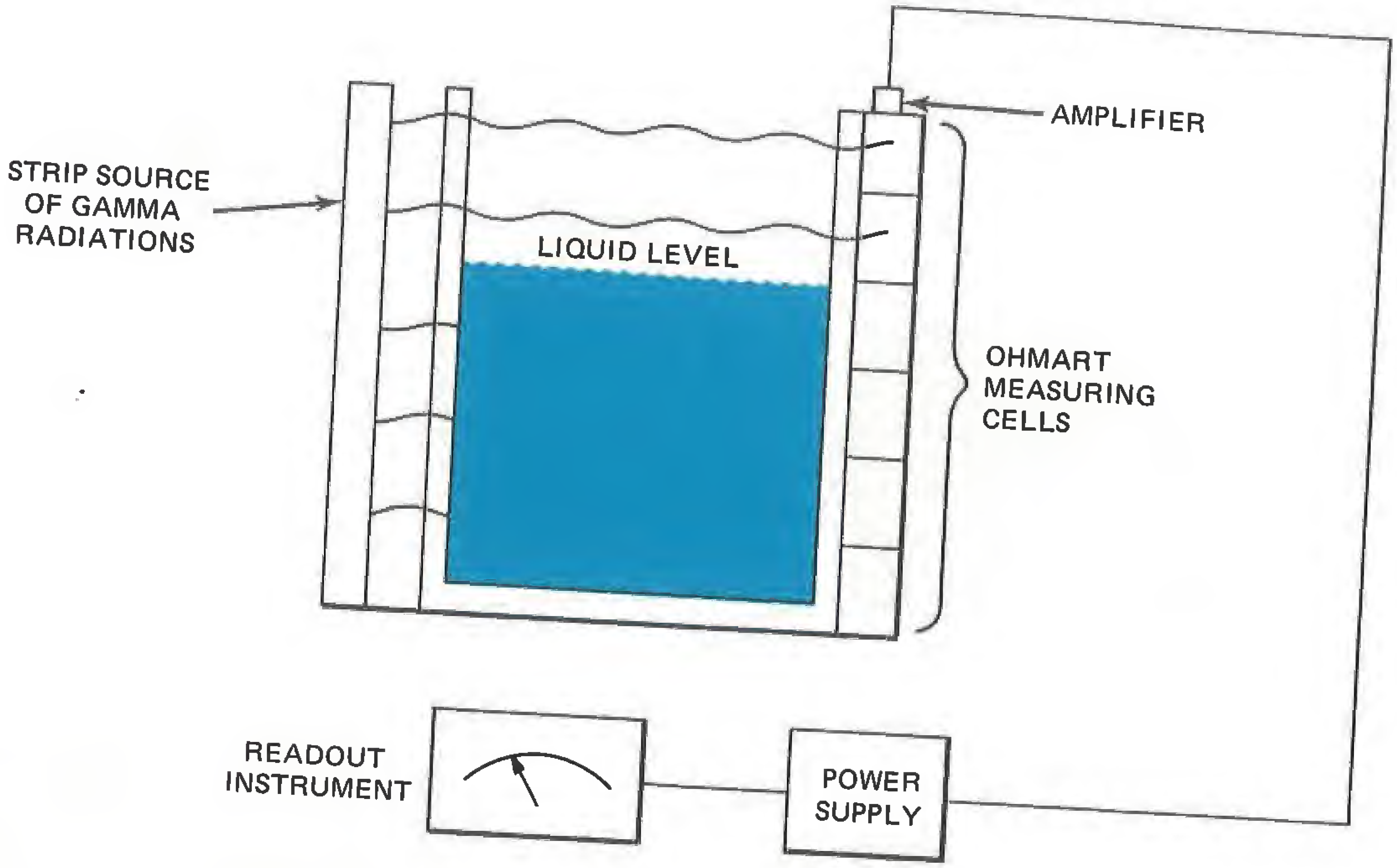


Fig. 11-9 Nuclear Liquid-Level Gage

diameter, and measure continuous heights of 20 feet and over to ± one percent repeatability.

Such a nuclear leveling device is shown in figure 11-9. The radioactive source is placed on one side of the tank and the detector on the other side. The liquid absorbs radiation as it rises and falls in the tank. The change in nuclear intensity received by the detector is a function of the liquid level.

The radioactive sources normally used are strontium 90 for beta radiation and cobalt 60 and cesium 137 for gamma radiation. The source is usually about 1 inch long and 1/8 inch in diameter with such rods placed end to end when needed. The source is usually housed in a shielded container with a rotary shutter for transmission purposes.

The detector used is normally a measuring cell which converts radioactive energy directly into electrical energy. The output is then fed to an amplifier.

Some of the advantages of this type of gage are:

1. No part of the gage is in contact with the material under measurement which keeps the gage independent of conditions such as high and low temperatures, pressure, viscosity, corrosion, and abrasion.
2. The repeatability is so great that the zero shift is frequently less than one percent of the scale in seven days.
3. No need for complex mechanisms.
4. Gages are ruggedly constructed.

Besides the other liquid-level devices given here, there are also ultrasonic systems used for measuring liquid levels. Sound waves are sent out to the surface of the liquid under measurement and are reflected back to the receiving unit. The level variation is measured by the time interval taken for the waves to travel to the surface and back to the receiver.

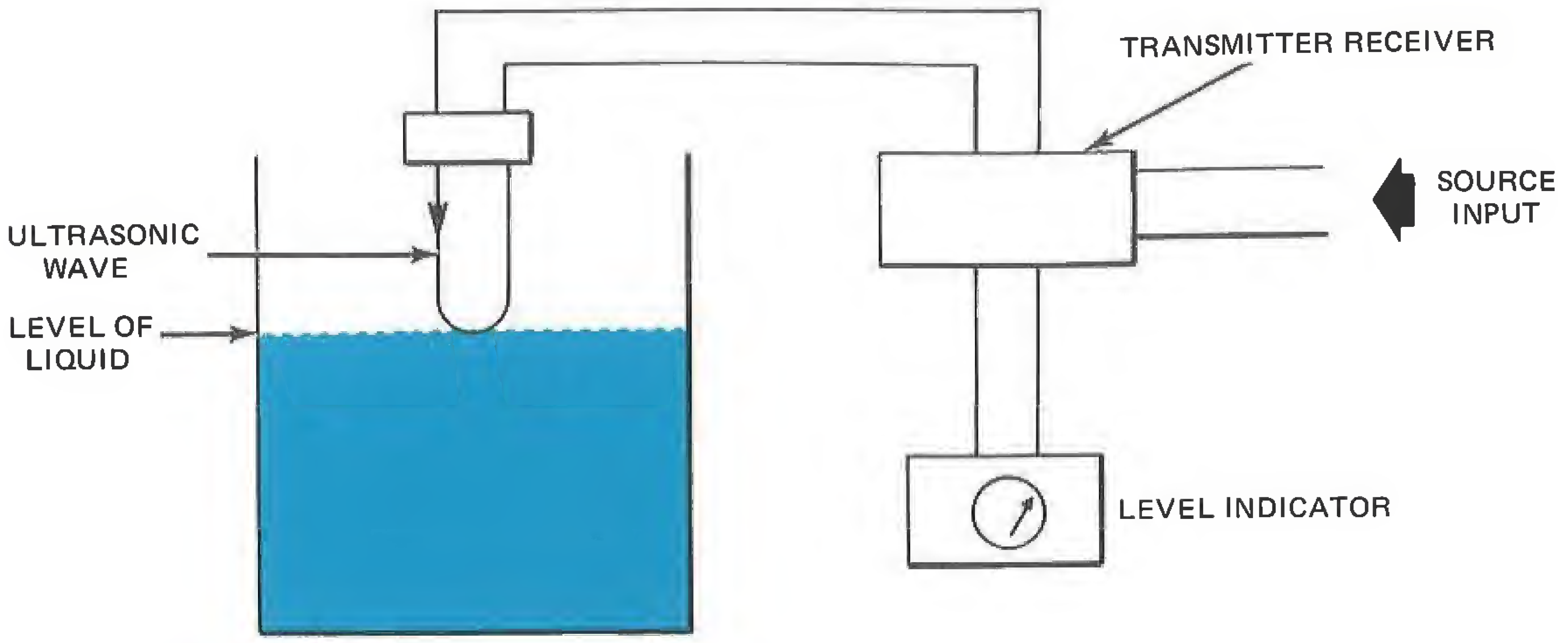
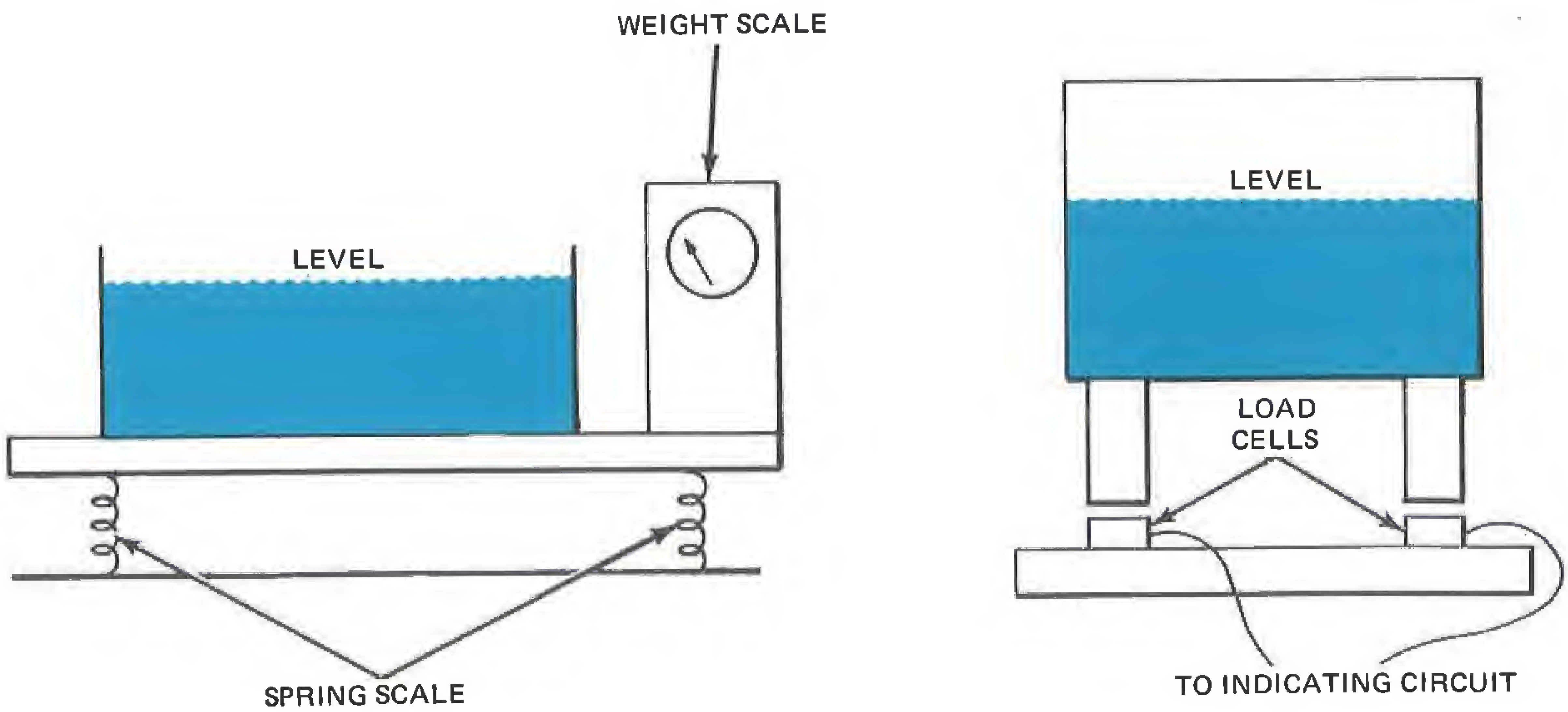


Fig. 11-10 Ultrasonic Liquid-Level Instrument

The farther away the liquid is, the longer it will take for the sound waves to return. This system is shown in figure 11-10.

Another method of measuring liquid level is to measure the weight of the entire vessel since the weight changes as the level of the material varies. The weight is measured using either mechanical scales or load cells. Load cells contain strain gages which provide a measurable electrical output proportional to the stress applied. As the weight of the vessel changes, the resistance of the strain gage changes. The resistance of the strain gage is recorded by way of a bridge circuit and a meter which is calibrated in units of level measurement. Since this method



(A) MECHANICAL SCALE USED IN LIQUID-LEVEL MEASUREMENT

(B) LOAD CELL LIQUID-LEVEL MEASUREMENT

Fig. 11-11 Liquid-Level Measurement by Weight Changes

requires that the change in weight be entirely dependent on the change in level, the substance being weighed must stay uniform in density and the moisture content must remain constant.

There are many other devices used for determining liquid-levels, the ones contained herein are very simple. However, they do represent a cross section of those most commonly used in industry.

MATERIALS

- 1 DC power supply (0 - 40V)
- 1 VOM or FEM
- 1 Precision potentiometer, 5 kΩ
- 2 Pulleys
- 1 Float
- 1 Five-gallon bucket
- 2 Weights
- 1 Length of string, 18 to 24 in.
- 1 12-in. ruler
- Materials to build test stand, bearings, braces, bolts and nuts as needed

PROCEDURE

1. Construct the test stand shown in figure 11-12.

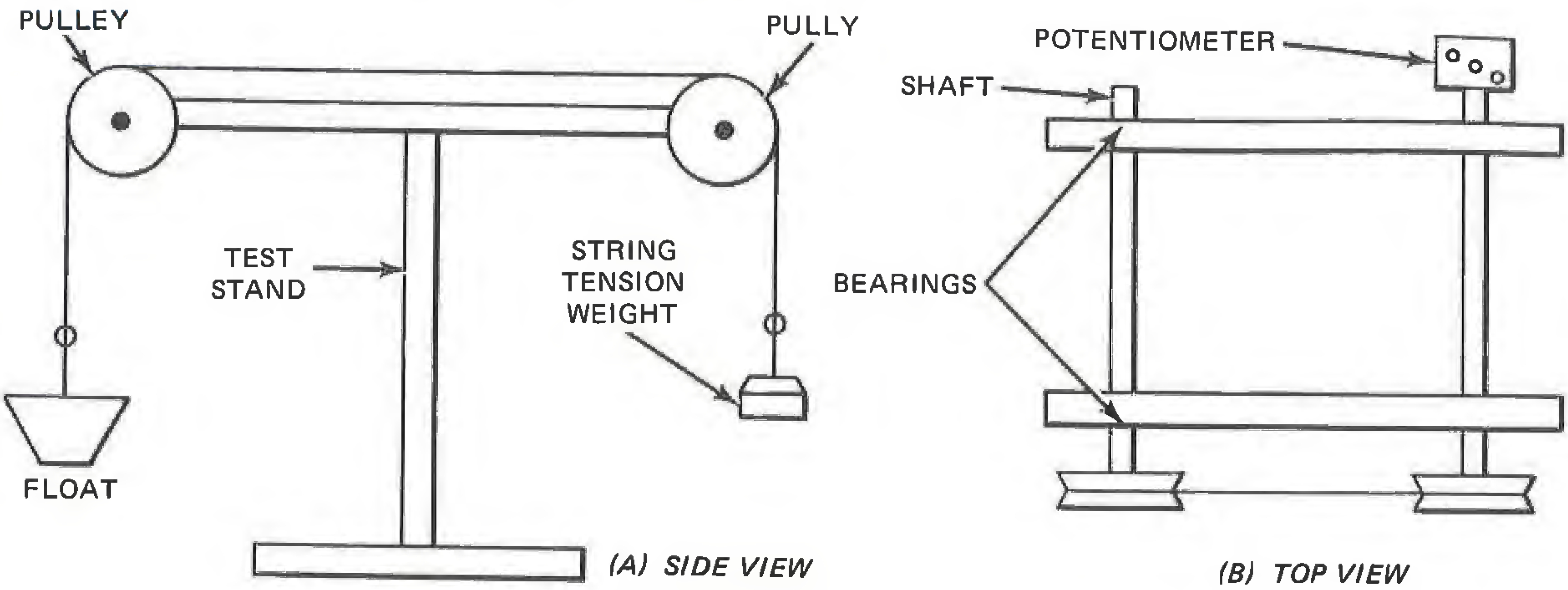


Fig. 11-12 Experimental Test Stand

2. When all the equipment is working correctly, the potentiometer should move easily as the float is raised and lowered.

3. Connect the potentiometer as shown in figure 11-13.

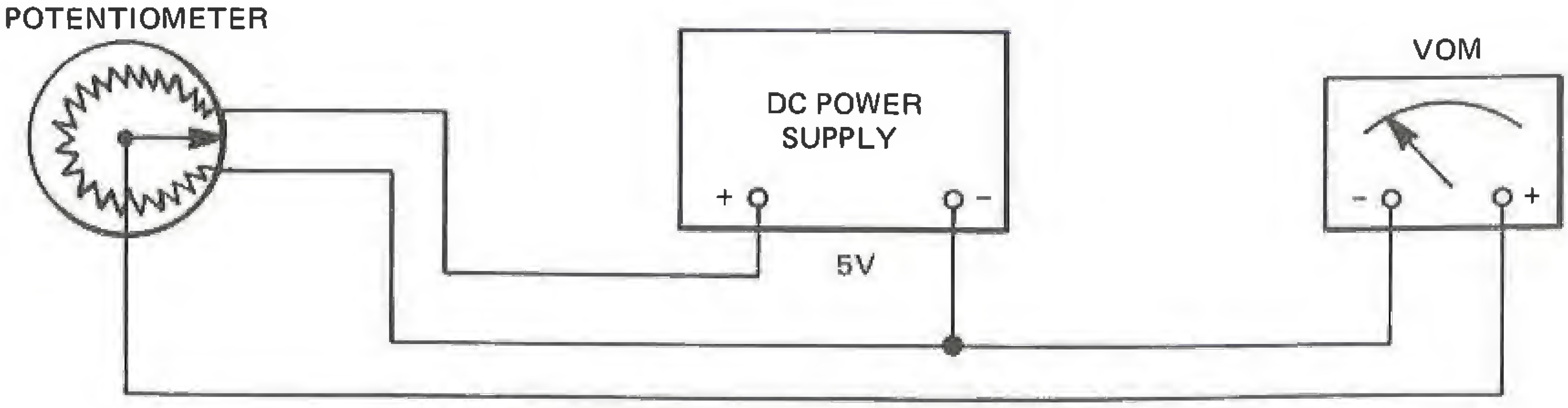


Fig. 11-13 Circuit Schematic

4. Place the bucket in such a position that the float will reach the bottom and will not touch the side.
5. Place the ruler in the bucket vertically so that the liquid level can be read.
6. Put about one inch of water in the bucket so that the float will be floating and not resting on the bottom.
7. Adjust the position of the pulley which drives the potentiometer so that five volts is indicated on the voltmeter.
8. Weight may need to be added to the float to overcome the effect of the string tension weight. It is important that the string tension weight not be so great as to help lift the float.
9. Place one more inch of water in the bucket.
10. Record the voltage output of the potentiometer in figure 11-14. Be sure that the string does not slip over the pulleys and that the pulleys run smoothly.
11. Raise the water level one more inch.
12. Record the voltage output.
13. Continue filling the bucket in one-inch increments until it is full. Record all voltages.

Depth inches	Voltage			
	Trial 1	Trial 2	Trial 3	Average
1	5	5	5	5
2				
3				
4				
5				
6				
7				
8				
9				
10				

Fig. 11-14 Data Table of Depth Versus Voltage Output

14. Empty the bucket.
15. Repeat the experiment two more times recording all voltages.
16. Calculate the average voltage for each depth of liquid.

ANALYSIS GUIDE. Plot a graph of average voltage versus inches of water in the bucket. Determine why the relationship is not linear. Explain how this particular apparatus could be adapted to measure the level of oil in a 15-foot storage tank.

PROBLEMS

1. What is the difference between a direct and an indirect level measuring device?
2. What is the name of the force which acts upon floats and displacer elements?
3. How many feet of water in an open tank would cause a pressure gage mounted at the bottom of the tank to read 25 psi? Use the density of water as 1.94 slug/ft^3 where one slug = lb-sec/ft.

experiment 12 *PHOTOELECTRIC TRANSDUCERS*

INTRODUCTION. With the coming of the Space Age and the need for energy generation in outer space, the use of photoelectricity became very important. In this experiment we will examine the characteristics and operation of a photoelectric transducer.

DISCUSSION. Electron emission from metals due to thermal agitation is known as thermionic emission. Electrons may also acquire enough energy to escape from a metal, even at low temperatures, if the material is illuminated by light of sufficiently short wavelength. This phenomenon is known as the photoelectric effect. It was first discovered by Heinrich Hertz in 1887 and later investigated by Hallwachs, to whom the discovery is usually credited. The solar sensor was soon discovered and shortly after that came the selenium light meter which is used extensively today by photographers.

Industrial applications make use of many photoemissive devices. Photoelectric devices are classified by the way the electric output is furnished to the circuit. Devices which emit electrons are *photoemissive.* Devices which change their resistance as a function of light intensity are *photoconductive* or *photoresistive.* Devices which produce potential differences are *photovoltaic.*

It has been found that with a given photosensitive material, the wavelength of light must be shorter than a critical value, which is different for each material. This critical wavelength, or the corresponding frequency, is called the threshold wavelength or frequency of the particular material. The threshold wavelength for most metals is in the ultraviolet spectrum (2000 - 3000 Angstroms where one Angstrom equals 10^{-10} meters), but for potassium and cesium oxide it lies in the visible spectrum (4000 - 7000 Angstroms).

Seen most often in "electric eyes", photoemission is a process whereby electron flow is generated when light strikes a light-sensitive surface. Figure 12-1 illustrates this phenom-

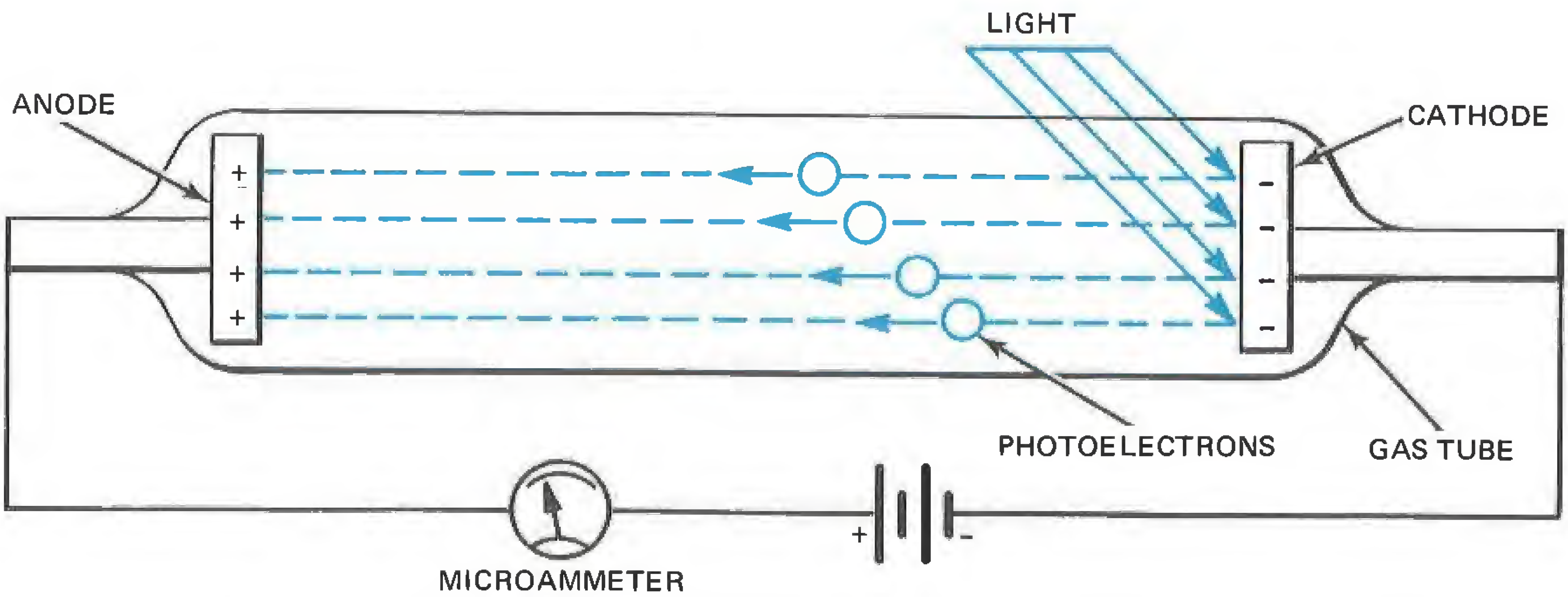


Fig. 12-1 Photoelectron Emission

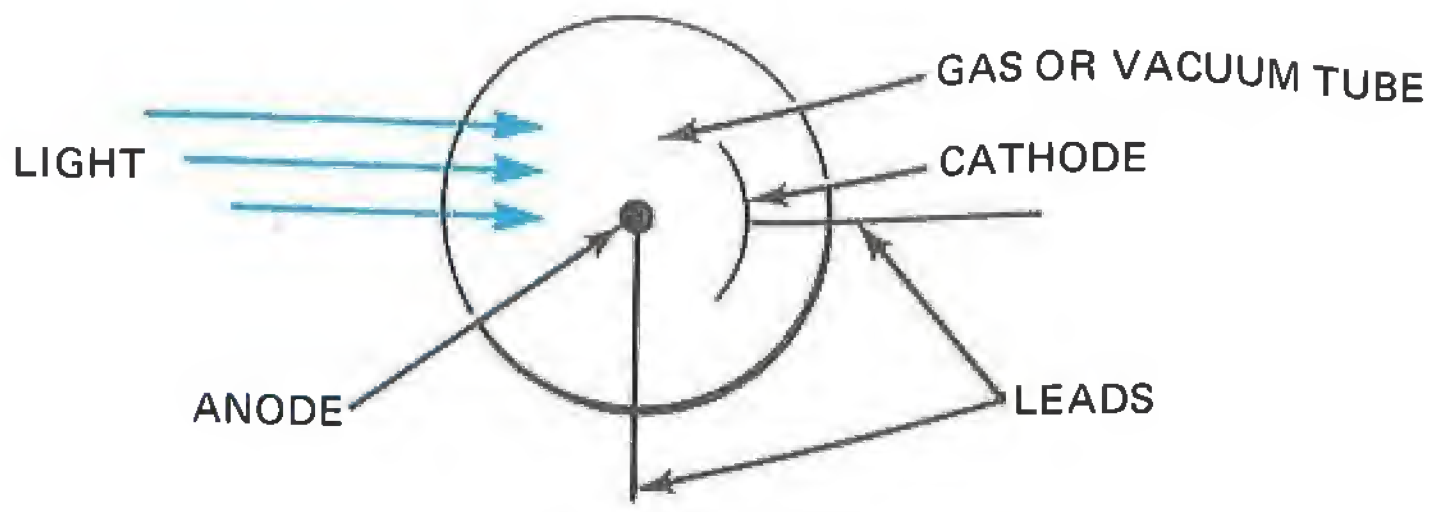


Fig. 12-2 Illustration of Photoelectric Tube

ena. The tube in figure 12-1 is a gas or vacuum tube with two metal plates. The cathode is made from light-sensitive material and it will give up electrons to the anode. A power supply must be connected so as to give the anode a positive charge and the cathode a negative charge. The device will not conduct until a light beam strikes the cathode surface and when it does, the molecular action within the material causes electrons to be freed from the cathode. These electrons are attracted to the anode. The electrons that are given off are called "photoelectrons." The internal resistance of a photoelectric cell (tube) is in the order of 10^{11} to 10^{12} ohms in darkness, which for practical purposes is an open circuit. Figure 12-2 shows another arrangement of a photoelectric tube.

The photoconductive cell's internal resistance changes with the light intensity falling on its photosensitive material. When operating at low light intensities the resistance is high. Photoconductive cells cover the entire spectrum from ultraviolet to infra-red. As pointed out before, each specific material to be used will possess a different response.

For these devices the long-wavelength limit is most often in the infra-red range between 10,000 and 8,000 Angstroms. Since the long wavelength limit is longer than the visible spectrum wavelengths, the photoconductive devices can be used in the visible as well as the ultraviolet regions. The sensitivity to infra-red radiation is of great practical importance. Photoemissive cells normally cannot compete in this region because there is not enough energy present. Therefore, photoconductive cells are most often used as infrared detectors.

Semiconductor photocells are perhaps the ones most often encountered. They have nonlinear and temperature-sensitive calibration curves and the choice of a suitable type depends on the particular use. Figure 12-3 shows a simple photoconductor circuit.

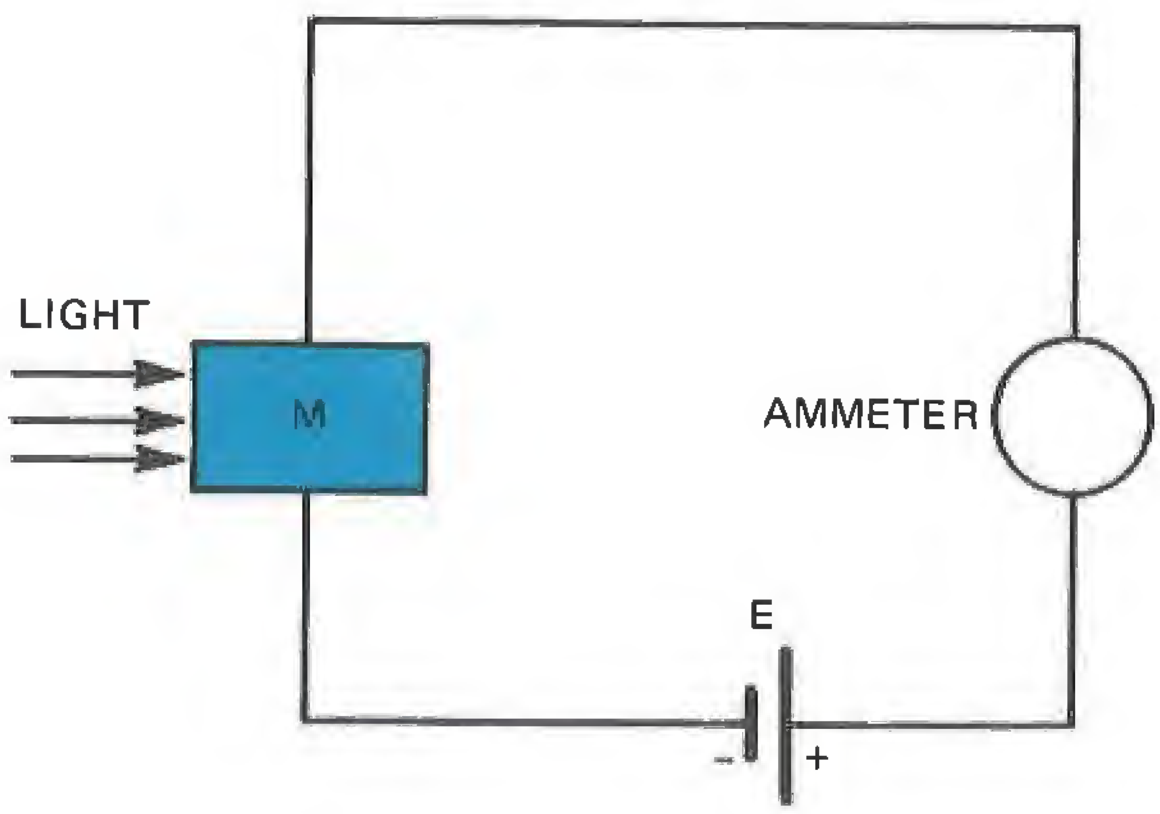


Fig. 12-3 Basic Photoconductor Circuit

While the material M, is in darkness, its resistance is high and very little current is flowing from the battery. When light strikes

Fig. 12-4 Symbol for Photoresistor

the surface of the material, the resistance will decrease and consequently the current will increase.

The photoconductive process is initiated by the absorption of an incident photon which causes excitation of an electron. The electron is then free to move. As more electrons are free to move, the conductivity of the device increases. As the conductivity increases, the resistance of the device decreases, allowing more current to flow.

The internal resistance of the photoconductor is in the order of 1×10^6 to 30×10^6 ohms in darkness. Figure 12-4 shows a symbol that is frequently used for a photoconductor (photoresistor).

A third type of photoelectric cell is one in which a voltage is produced directly by the application of light upon the photosensitive material. The most important of this class is the dry type, or the barrier-layer type, in which the light acts upon the boundary layers between a metal and a semi-conductor.

Figure 12-5 shows a cut-away view of a selenium-on-iron cell which is often used in commercial photographic exposure meters and in foot-candle meters. In this cell the selenium is placed on an iron disc and then a thin translucent layer of metal, such as gold or silver, is placed on the selenium to act as a front electrode.

As light strikes the light-sensitive material the electrons near the front electrode tend to be displaced from the selenium to the metal electrode. The electrons cannot return easily through the boundary, so they return through the external circuit. If the circuit is open, the electron flow across the barrier will increase the difference of potential between the terminals until an equilibrium is reached and the net electron flow is zero.

The potential produced is relatively small and is not a linear function of the illumina-

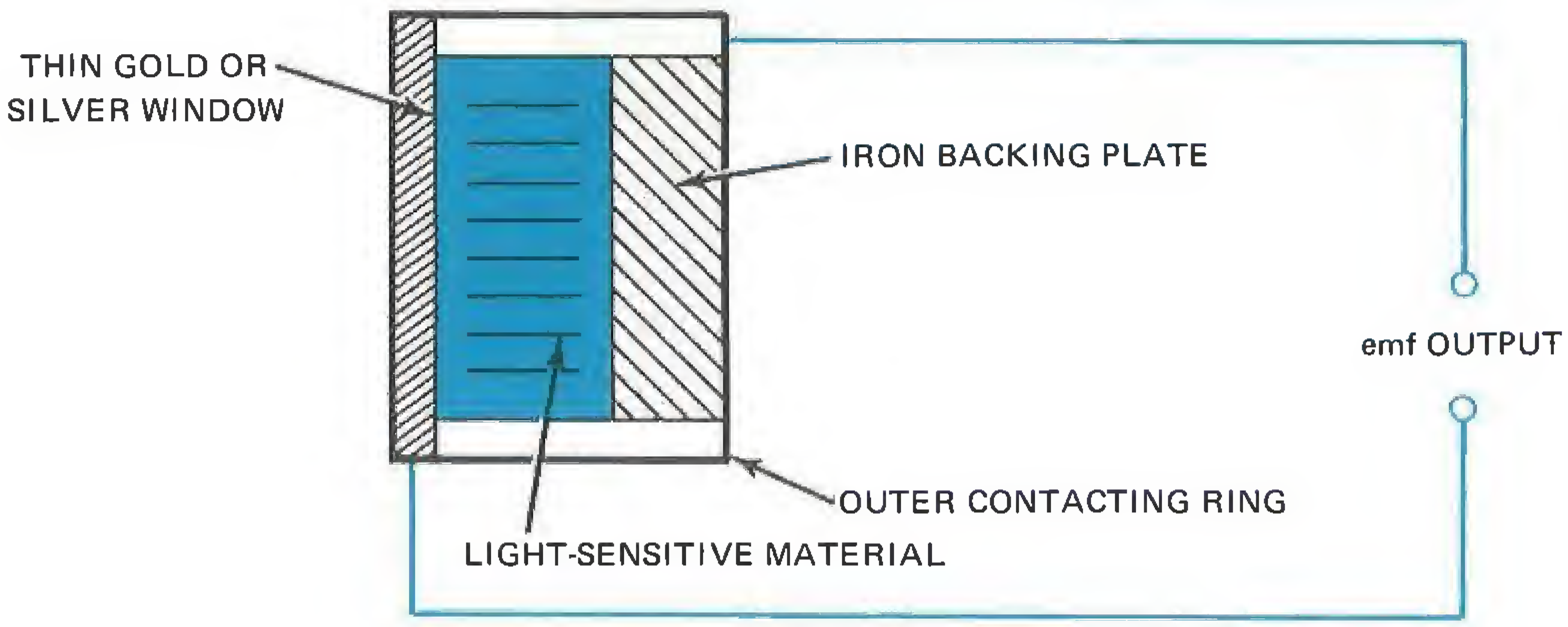


Fig. 12-5 Basic Photovoltaic Cell

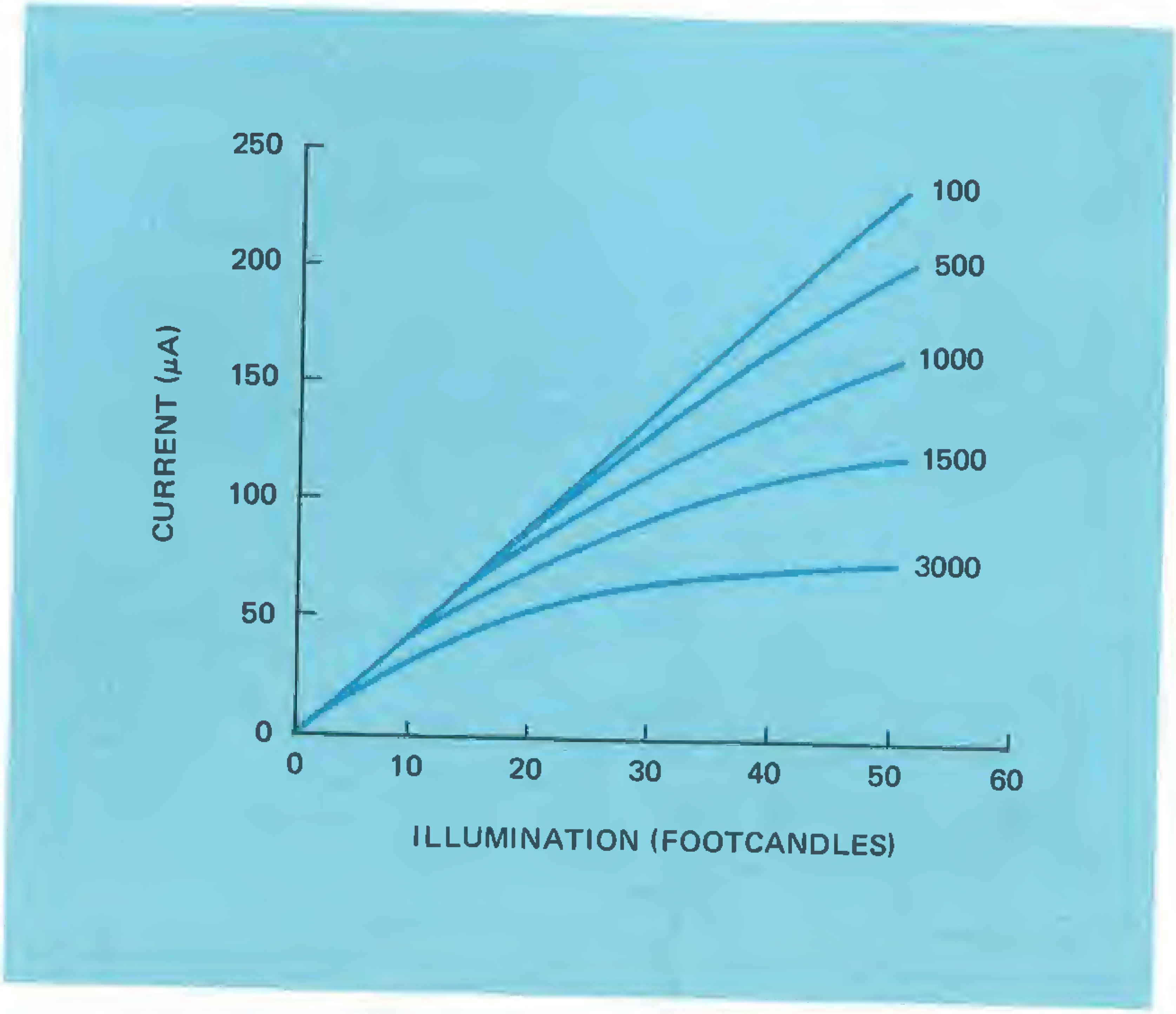


Fig. 12-6 Output Current for a Typical Photovoltaic Cell

tion. However, if the cell is connected to a low resistance microammeter, the circuit current is nearly a straight-line function of the illumination. The behavior of the cell is shown in figure 12-6 with the current as a function of the illumination, and the external resistance as an additional variable.

The photovoltaic cell can generate enough power to actuate a relay. The relay must be very sensitive and its resistance must be chosen so that the cell delivers approximately maximum power output. These relays are usually slow in action and are normally used where high speed is not essential.

The photovoltaic cell can be used as a source to produce electrical energy. In the space industry they are called solar cells. Through these cells, scientists have been able to put man into space and recharge the batteries on board his space craft everytime the craft is sunlit.

Because small voltages and currents are produced from fairly large-sized cells, about 0.6 volts per cell in full daylight, many cells are required to produce appreciable power.

The internal resistance of this device is in the range of 300 to 6000 ohms, and its surface temperature should not exceed 122°F.

Photoelectric cells of one type or another are being used in many places around the home and community. Some examples are the automatic eye which controls outside lights around the home, automatic opening and closing of doors at the supermarket, burglar alarms in various establishments, flame indicators for fire alarms, heat control, and also fluid level controllers.

MATERIALS

1 VOM or FEM
2 Photovoltaic cell
1 Photoconductive cell
1 20Ω Resistor

1 Light source (75- to 150-watt lamp)
1 Meter stick
3 Sheets of white paper
1 Sheet of black paper

PROCEDURE

1. Set up the apparatus shown in figure 12-7 with one of the photovoltaic cells.

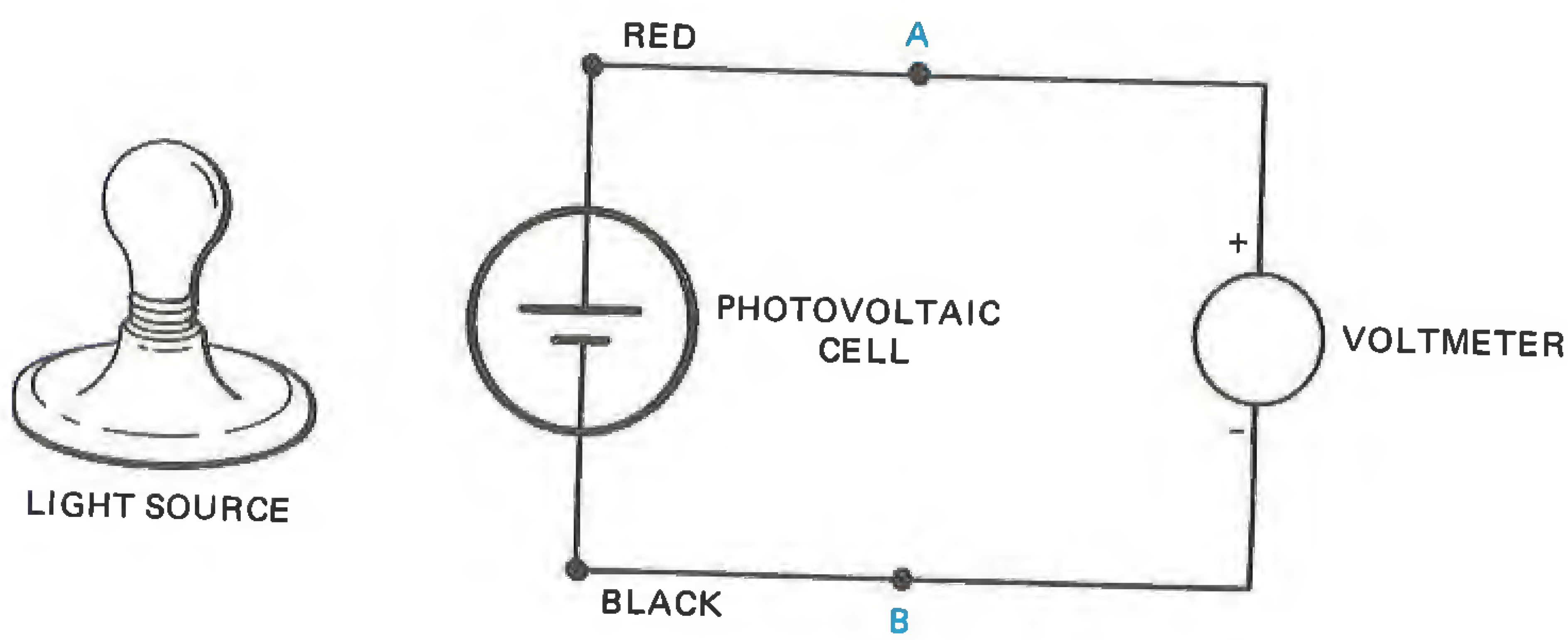


Fig. 12-7 Photovoltaic Circuit

2. With the light source off, place a sheet of black paper over the photovoltaic cell. Measure the voltage and record in the data table, figure 12-9.
3. Remove the paper and record the voltage for normal room light.
4. With the light source on, record the voltage for distances of 4, 3, 2, 1 and one-half feet between the light source and the cell.
5. Replace the cell with the other photovoltaic cell.
6. Repeat steps two, three and four.
7. Place a 20-ohm resistor between points A and B of figure 12-7.
8. Repeat the experiment recording the voltage in the data table.
9. Calculate the current and power for each set of data.
10. Set up the circuit with the photoconductive cell as shown in figure 12-8.
11. With the light source one foot away, place one sheet of white paper between the light source and the cell.
12. Record the resistance in the data table, figure 12-10.
13. Repeat for two and three sheets of paper.

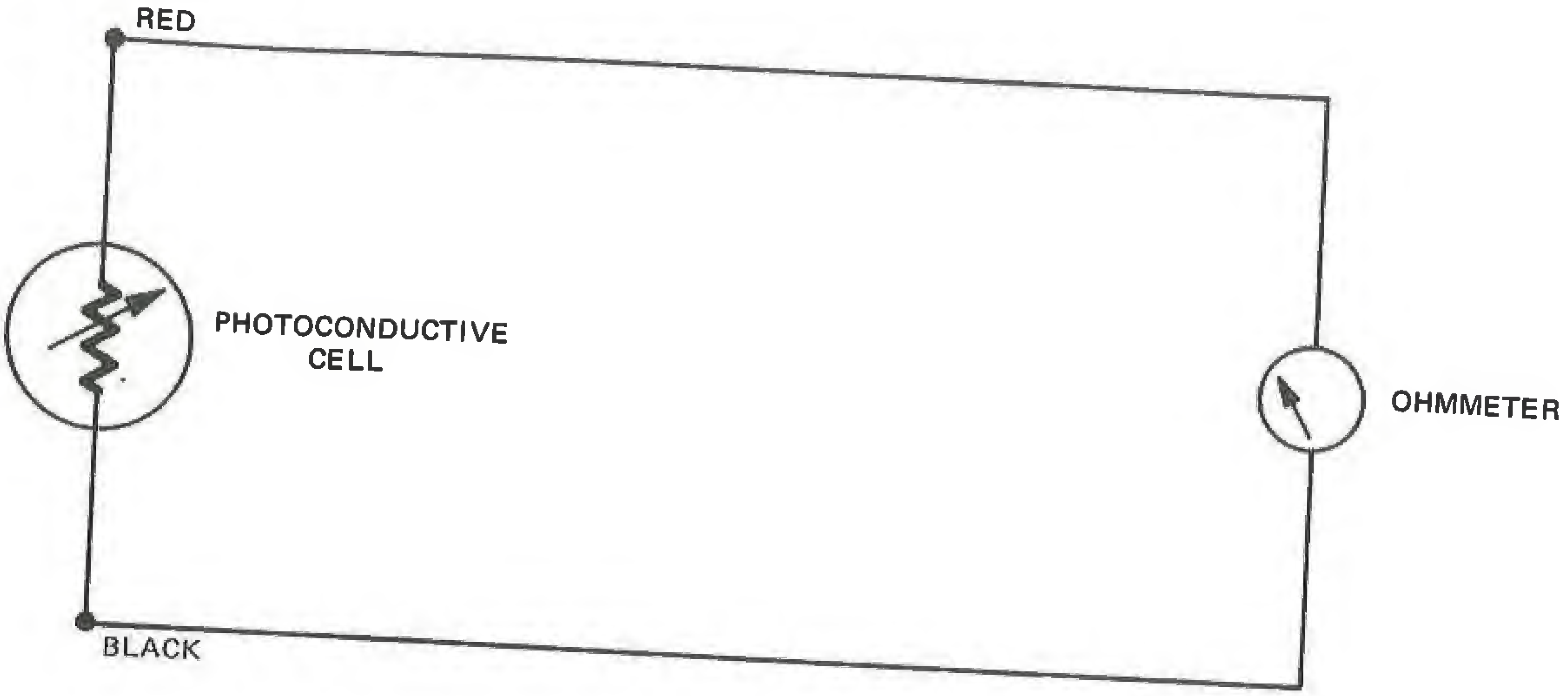


Fig. 12-8 Photoconductive Circuit

No. of Sheets	1	2	3
Voltage			

Fig. 12-9 Voltage Output Versus Obstruction

	Black Paper	Room Light	4 ft	3 ft	2 ft	1 ft	6 in.
Photovoltaic One							
Photovoltaic Two							
With 20Ω Resistor (Voltage)							
Current (mA)							
Power (mW)							
Photoconductor							

Fig. 12-10 Voltage Output Versus Illumination

ANALYSIS GUIDE. Plot graphs of the voltage output versus illumination distance. Also plot a graph of voltage output versus the obstructions for the photoconductive material. It should be apparent from the graphs that the voltage and illumination are related.

PROBLEMS

1. How many cells hooked in series like the first photovoltaic cell would be needed to produce five volts at a distance of two and a half feet from the light source used?
2. Give two applications of a photo cell used in the community.
3. Draw a circuit for each application given.

experiment 13 PHOTOCELL APPLICATION

INTRODUCTION. The applications of photocells in industry are numerous and varied. In this experiment we will examine a few of the basic uses of the photocell.

DISCUSSION. The photocell is used as a control device because of its diversified characteristics. A review of these characteristics is important.

The photoemission cell gives off electrons from one plate to another when illuminated by a light source. The plates require an initial voltage applied to them and the electrons emitted are called photoelectrons.

The photoconduction cell acts as a variable resistor. When light falls upon its sensitive material, the resistance of the device goes down, allowing more current to flow in the external circuit. The phototransistor is a good example of the photoconductor.

The photovoltaic cell is primarily a voltage source. This device produces a potential (emf) when light falls upon its photosensitive material. This device does not require an external source like the photoemission cell. The photographer's "electric eye" is an example of this device. Several of these cells can be placed in series to make up what is known as a solar cell.

Before examining applications of the various photocells, some fundamentals of photoelectric emission will be discussed.

Light, and electromagnetic radiation, is a form of energy. This energy can be considered to be made up of discrete packages. The energy per package is related to the frequency of the light by

$$\boxed{\text{Energy} = hf \text{ (quantum energy or joules)}} \tag{13.1}$$

where h is Planck's constant (6.624×10^{-34} joules per second) and f is the frequency of radiation in Hertz.

Each package of energy is called a *photon* and the amount of energy is called a *quantum.* If the energy in a photon striking a metal surface is equal to or greater than the work function of the metal, an electron will be emitted.

Einstein developed this mathematically as

$$\boxed{hf = eE_W + \frac{mv^2}{2} \text{ joules}} \tag{13.2}$$

where

E_W = energy of the work function

m = mass of the electron, kg

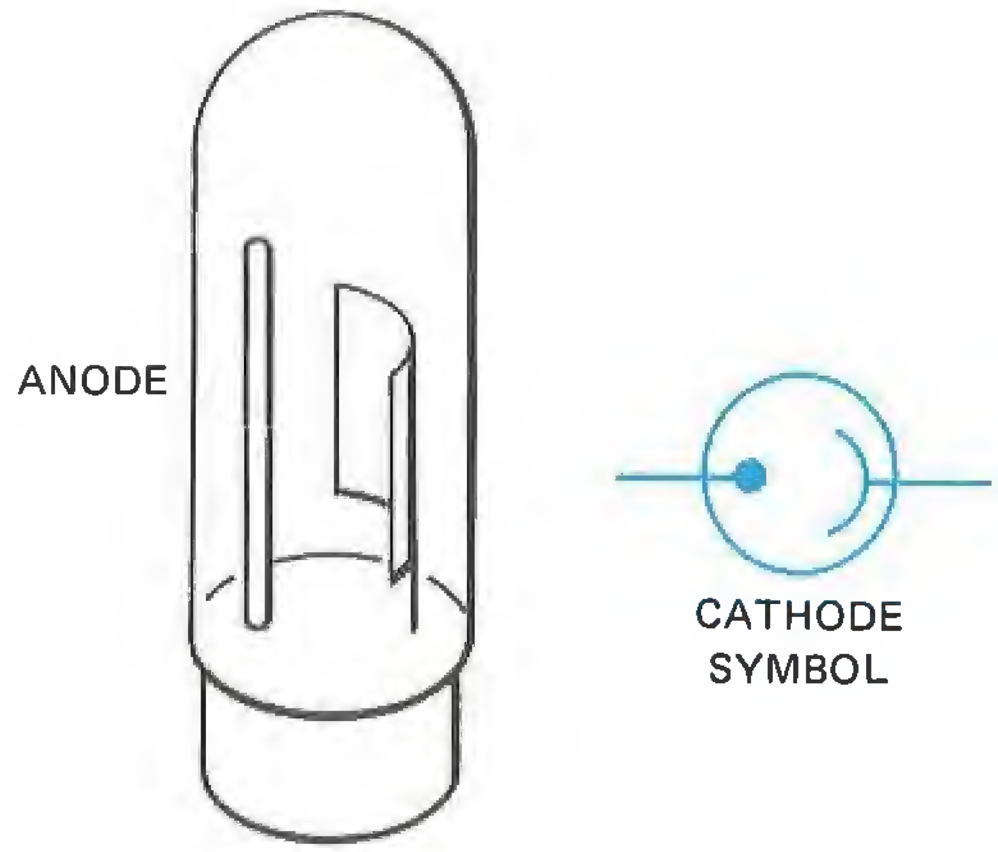
v = velocity of the electron, meters/sec

e = 1.6×10^{-19} coulombs

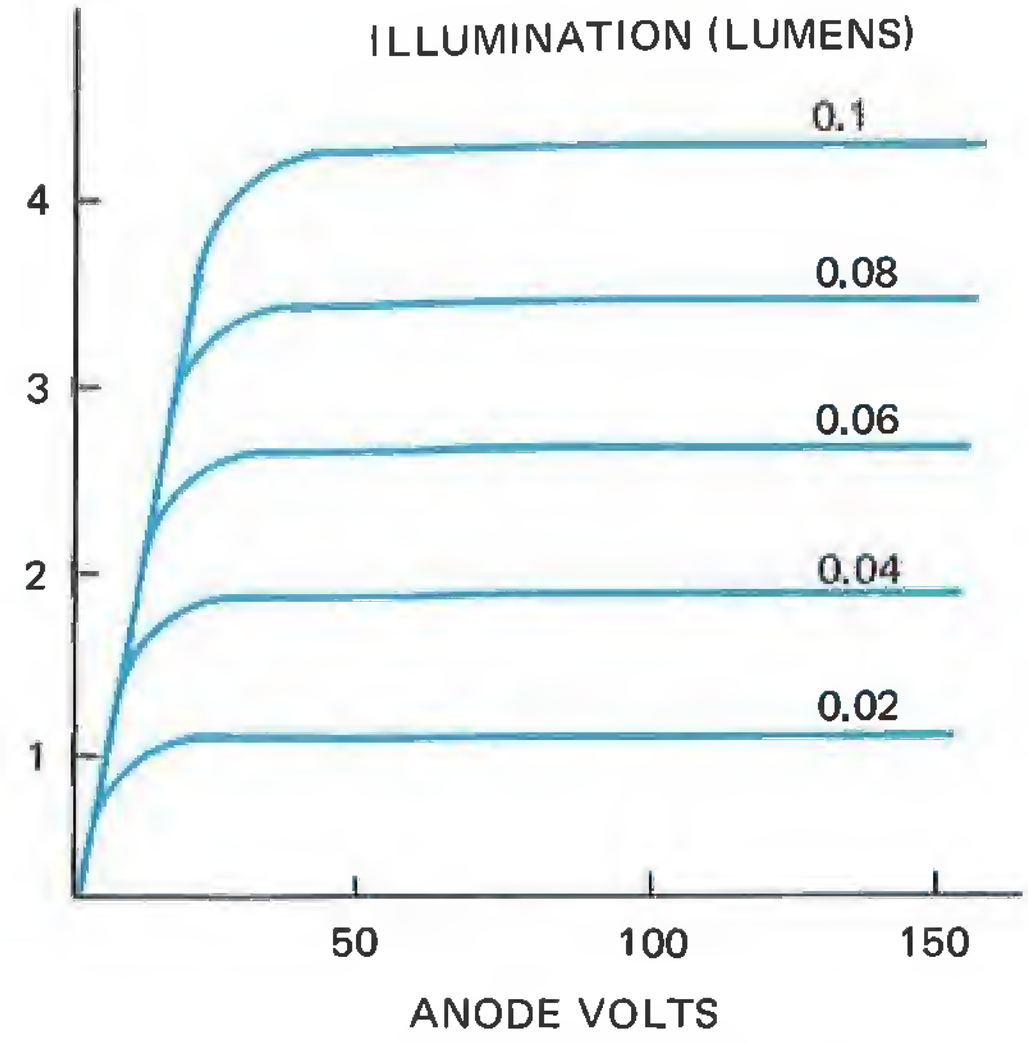
For any given photosensitive material, the work function is a constant. Therefore, there must exist a frequency of radiation (threshold frequency) below which emission will not occur. At the threshold frequency, the emitted electrons have no kinetic energy so equation 13.2 becomes

$$\boxed{f_o = \frac{eE_W}{h}} \tag{13.3}$$

where f_o = threshold frequency.



(A) TYPICAL PHOTOTUBE



(B) AVERAGE ANODE CHARACTERISTICS

Fig. 13-1 Typical Phototube and Characteristics

For emission to occur, it is necessary to have a work function equal to or less than the radiant energy of a photon. Metals with this characteristic are cesium, potassium, rubidium, sodium, and lithium, all combined with oxygen or hydrogen.

To illustrate the use of these equations, let's determine the work function of a metal which gives off an electron with an energy of 0.68 electron volts when it is exposed to light having a frequency of 8.2×10^{14} Hertz. Using equation 13.2 we have

$$hf = eE_W + \frac{mv^2}{2}$$

Solving for E_W gives

$$E_W = \frac{hf}{e} - 0.68$$

$$E_W = \frac{6.624 \times 10^{-34} \times 8.2 \times 10^{-14}}{1.602 \times 10^{-19}} - 0.68$$

$$E_W = 3.33 - 0.68$$

$$E_W = 2.65 \text{ electron volts}$$

Figure 13-8A illustrates a typical photoemissive tube.

In a typical photoemissive cell, the cathode is semicircular in shape and the anode is a rod. When incident light strikes the cathode, electrons are emitted. A positive voltage applied to the anode will create a current. As the voltage is increased the current will increase and eventually level off and remain constant. Figure 13-1B shows a series of typical output waveforms for various intensities of light.

One application of a photoemissive cell is in the operation of a relay. The relay could further be used to turn street lights on and off, dim the lights of an automobile or send a signal to the police or fire department.

Figure 13-2 shows a typical circuit for operating a relay. A transistor is used to amplify the output of the phototube. Before light strikes the cathode of the phototube there is only leakage current (I_o) from B to E.

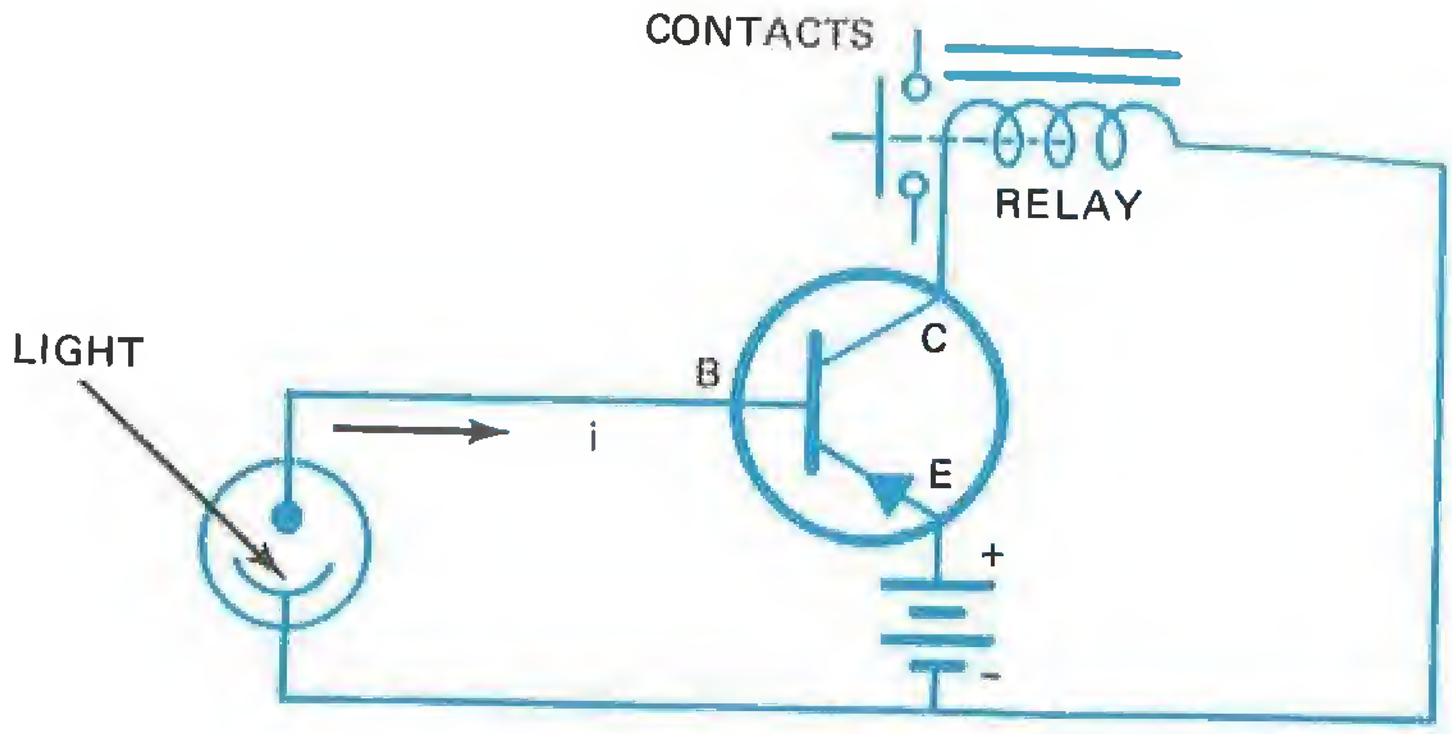


Fig. 13-2 Phototube Circuit with a DC Relay

Therefore, there is only β times I_O flowing through the relay. Assuming this is not enough current to activate the relay, the relay will remain in its present state. When the light strikes the photocell, more electrons begin to move to the anode and current is increased. When this current (i) times the gain of the transistor (β) becomes great enough, the relay will activate.

Let's determine how much photocell current is needed to activate a relay that operates at 50 milliamps; assume that β is equal to 100.

$$i\beta = \text{required relay current}$$

$$100i = 50 \text{ mA}$$

$$i = \frac{50 \text{ mA}}{100}$$

$$i = 0.5 \text{ mA}$$

The current from the photocell must be at least one-half milliamp to activate the relay.

In most applications, we choose the photodevice on the basis of the light source and the degree of variation of the light. The selection specifies the size of supply voltage and the gain of the amplifier needed.

The relay used in figure 13-2 may be used to either open or close a switch depending on how it is wired. If the circuit is used to activate a dimmer switch in a car, the relay would close with an increase in light intensity. This is the way in which most counting, sorting, and burglar alarm systems work.

If the light intensity in figure 13-3 is sufficient, a current will flow and the relay

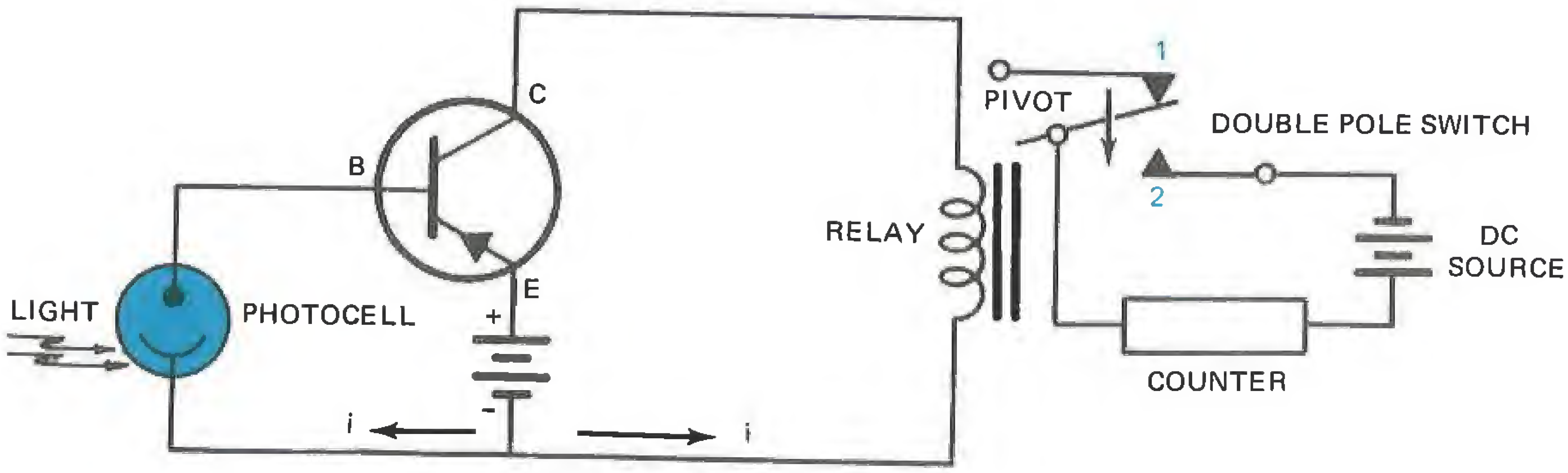


Fig. 13-3 Photocell Circuit Used in Counting Machine Parts

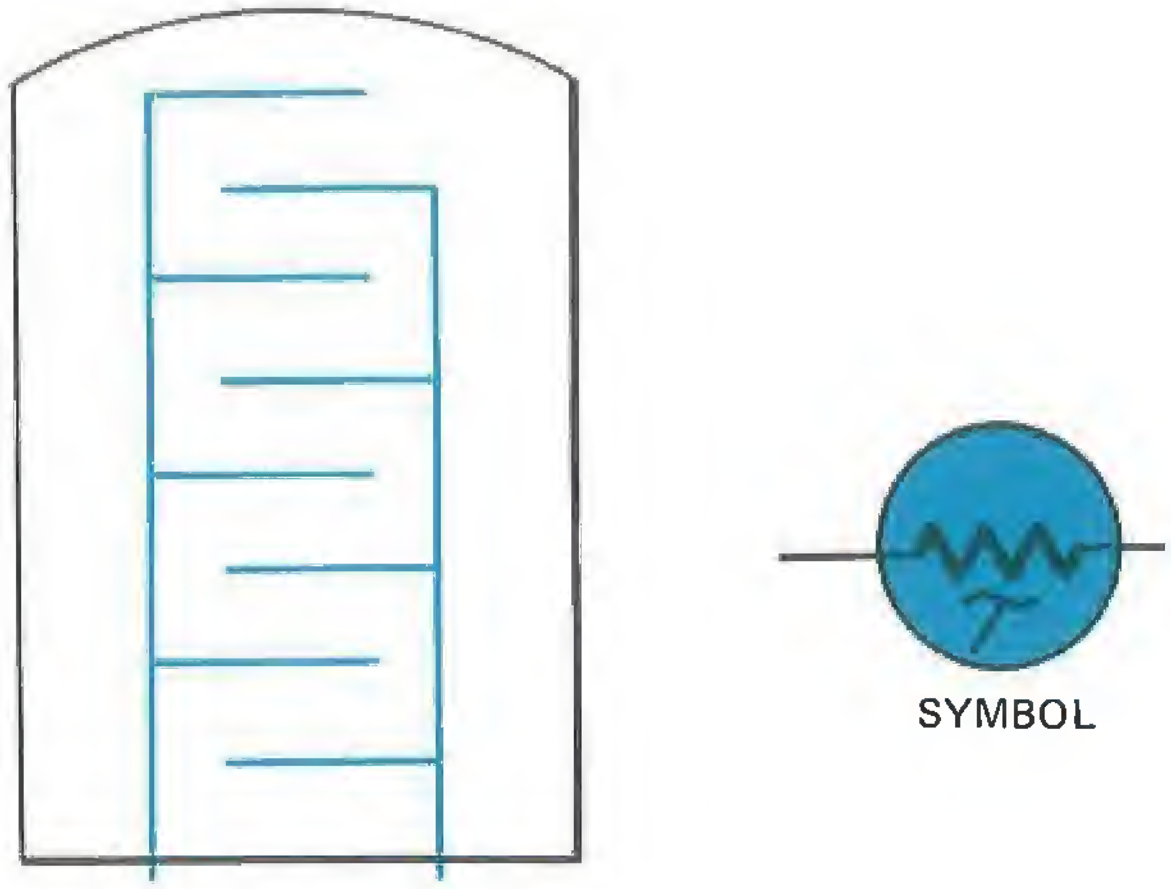


Fig. 13-4 Typical Photoconductor-Cell and Symbol

will hold the switch in position one. If a part on an assembly line moves between the light source and the photocell, the current will momentarily be cut off, and the relay will move to position two. When the relay is in position two, the counter circuit is complete and the counter will record the part. When the part moves past the light source, the relay again moves to position one and the circuit is ready to count the next part.

The principle of operation of a photoconductive cell depends on a decrease in resistance with increased light intensity. When light strikes a photosensitive material such as

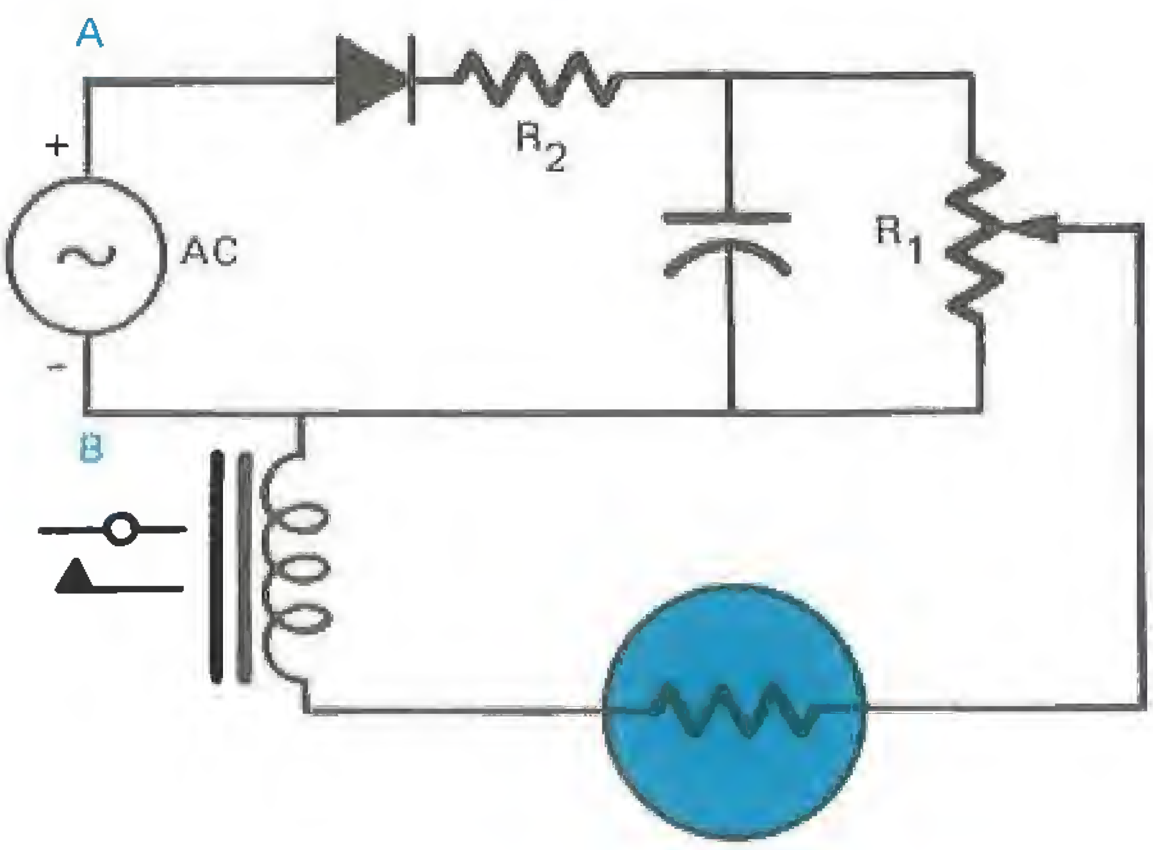


Fig. 13-5 Typical Photoconductive Circuit

cadmium, selenium, and lead sulfide, electrons are freed. This freeing of electrons increases the conductivity of the material which lowers its resistance. Commercial cells have approximately 5 to 10 megohms resistance when in the dark, as compared to one-half to one megohm when exposed to normal daylight.

A typical cell would look like the one in figure 13-4. This cell might be made of selenium and have short conduction paths of large cross-sectional area. In this particular cell, two conducting layers are separated by a thin layer of selenium. When a number of cells like this are placed in parallel, currents of up to one-half amp can be used.

Cadmium sulfide cells are also frequently used. The dark resistance of this cell may be 100,000 times greater than its resistance when illuminated. The advantage of the cadmium sulfide cell is that it can control relays without using an amplifier. Figure 13-5 shows a circuit used in operating a relay which turns street lights on and off.

In this circuit when A is positive with respect to B, electrons flow from B through the relay and also through the capacitor. Because of the high resistance of the photoconductor, the current is not enough to activate the relay. On the other half-cycle, B positive with respect to A, the diode is reverse-biased and only leakage current flows. The capacitor discharges through the resistor R_1 and the relay. But again the high resistance of the cell allows only a small current to flow through the relay.

When a light source illuminates the cell, the process is different. The resistance of the cell goes down, the current from the source

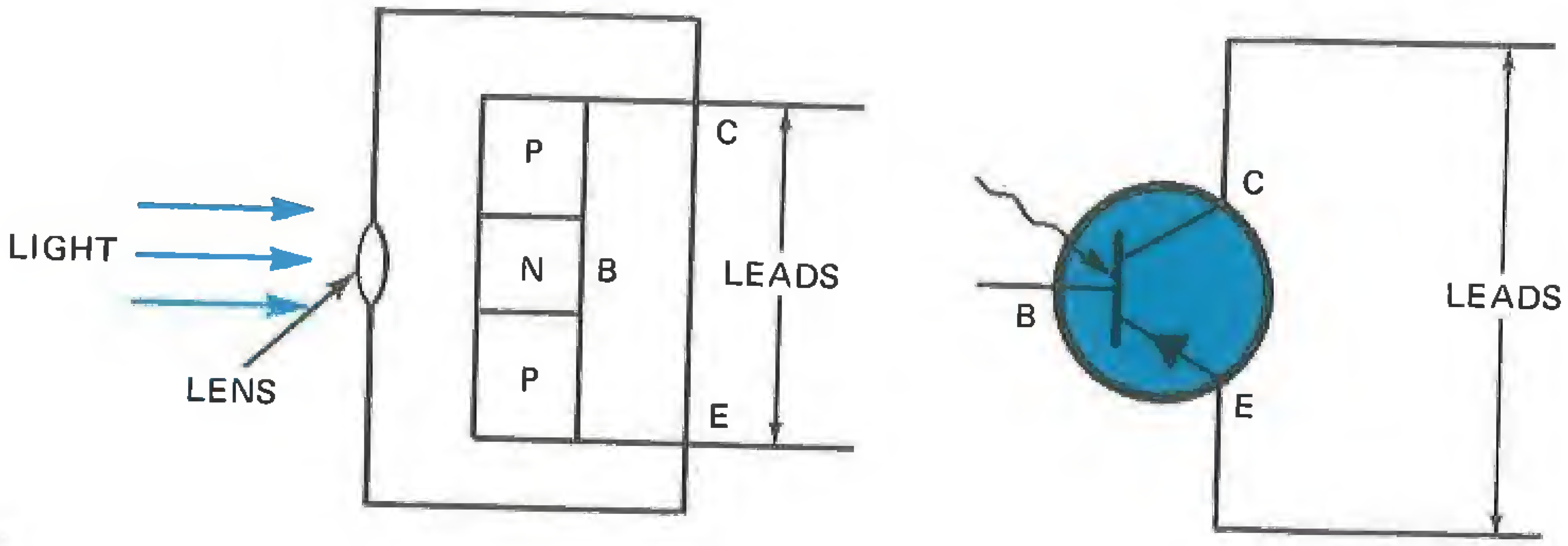


Fig. 13-6 A Schematic of a Phototransistor

activates the relay. When the diode blocks the source current on the negative half-cycle, the discharging current from the capacitor keeps the relay energized. When this circuit is used as a light control for street lights, the relay is wired so that with daylight illumination, the relay will hold the light circuit open. When the light dims, the resistance of the photocell will increase, decreasing the current to the relay which will cause it to close the light circuit. The circuit is located above the luminaire so that it is not affected by the street lights.

The phototransistor is another example of a photoconductor. The phototransistor is shown in figure 13-6. It is a transistor with a light-sensitive base. Light beams shine on the junction between E and B causing the depletion region of the junction to decrease, which in turn allows electrons to flow. As the light intensity increases, the electron flow increases.

Figure 13-7 shows a circuit using this phototransistor. With no light at B, the phototransistor is not conducting. All the voltage E_{DC} appears between the emitter and the collector of the phototransistor. Kirchhoff's voltage law for this loop circuit is

$$E_{DC} = iR_L + iR_{CE} \qquad (13.4)$$

When R_{CE} is much greater than R_L, most of the voltage is dropped across R_{CE}.

As the light intensity is increased, the resistance from C to E (R_{CE}) decreases. As R_{CE} decreases, the voltage drop across R_L increases. When the voltage across R_L

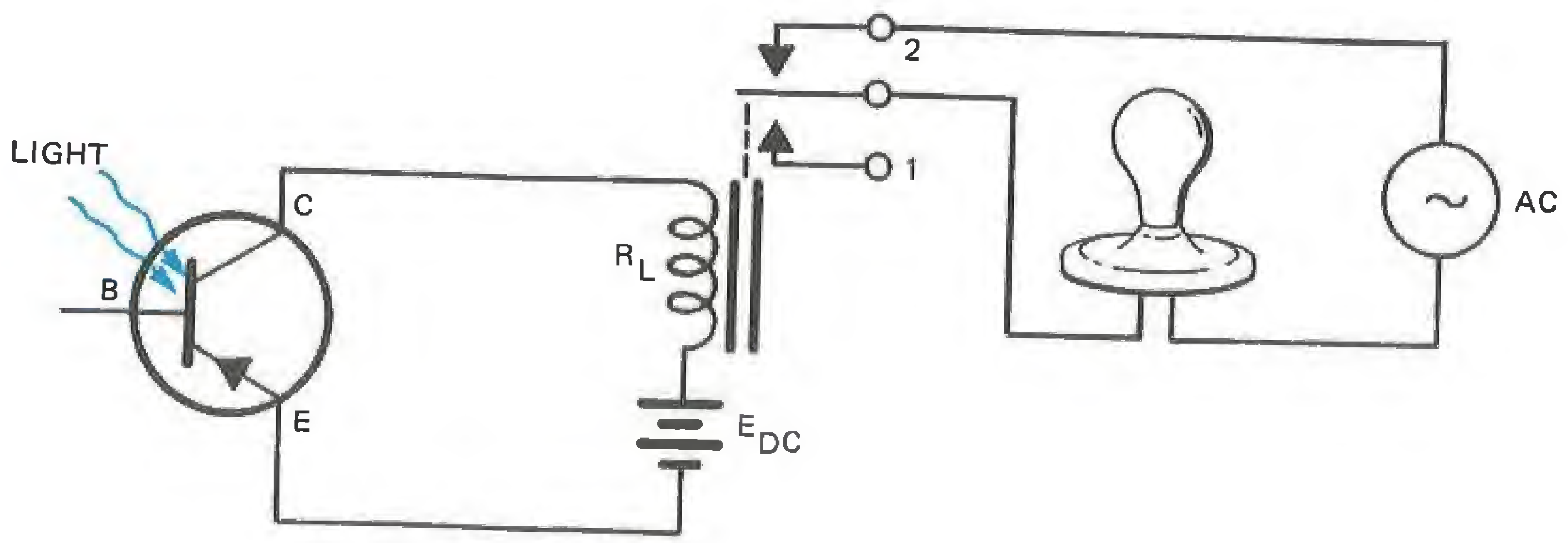
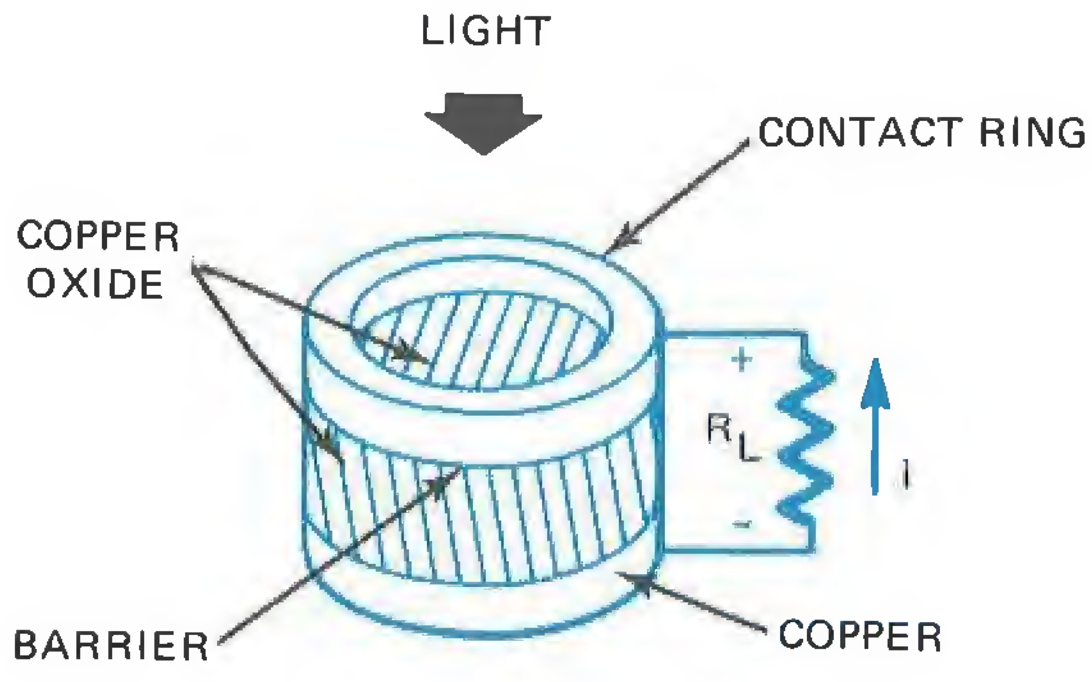
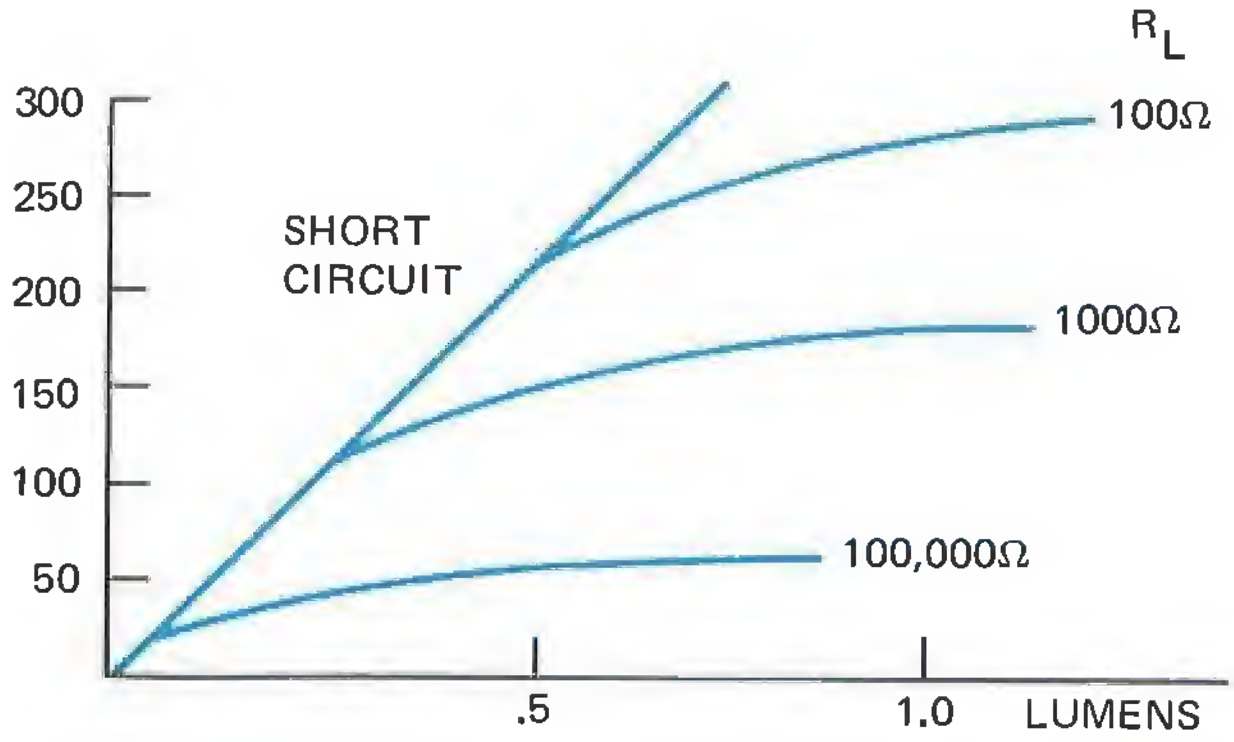


Fig. 13-7 Phototransistor Circuit as a Light Control



(A) PHOTOVOLTAIC CELL



(B) TYPICAL RESPONSE OF CURRENT VERSUS LUMENS

Fig. 13-8 Barrier-Layer Cell and Typical Output Waveforms

becomes great enough, the relay moves to position one, cutting off the lights. When darkness comes again, the voltage across R_L drops and the relay moves to position two, turning the lights on again.

The photovoltaic cell is sensitive to light and, unlike the phototransistor or photoresistor, it produces a voltage without external source.

There are two basic types of photovoltaic cells, the wet cell and the dry or barrier-layer cell.

Although the wet cell was developed first, the more efficient barrier-layer cell has replaced it in most applications. The barrier-layer cell is what is used for photographic equipment. Figure 13-8a shows a schematic of a barrier-layer cell.

When light strikes the copper oxide, electrons above the barrier cross over into the copper base. The copper base becomes negatively charged with respect to the contact ring. Electrons begin to flow through the short circuit from the copper base to the contact ring. A graph of the current produced versus the light in lumens is shown in figure 13-8B. For a linear response to the light, the load resistor R_L should be as small as possible.

An increase in sensitivity can be obtained by placing the barrier-layer closer to the light as shown in figure 13-9. Light passes through the transparent electrode creating two voltages, one between the selenium compound and the electrode, and the other between the barrier-layer and the electrode. The output voltage is the difference of the two.

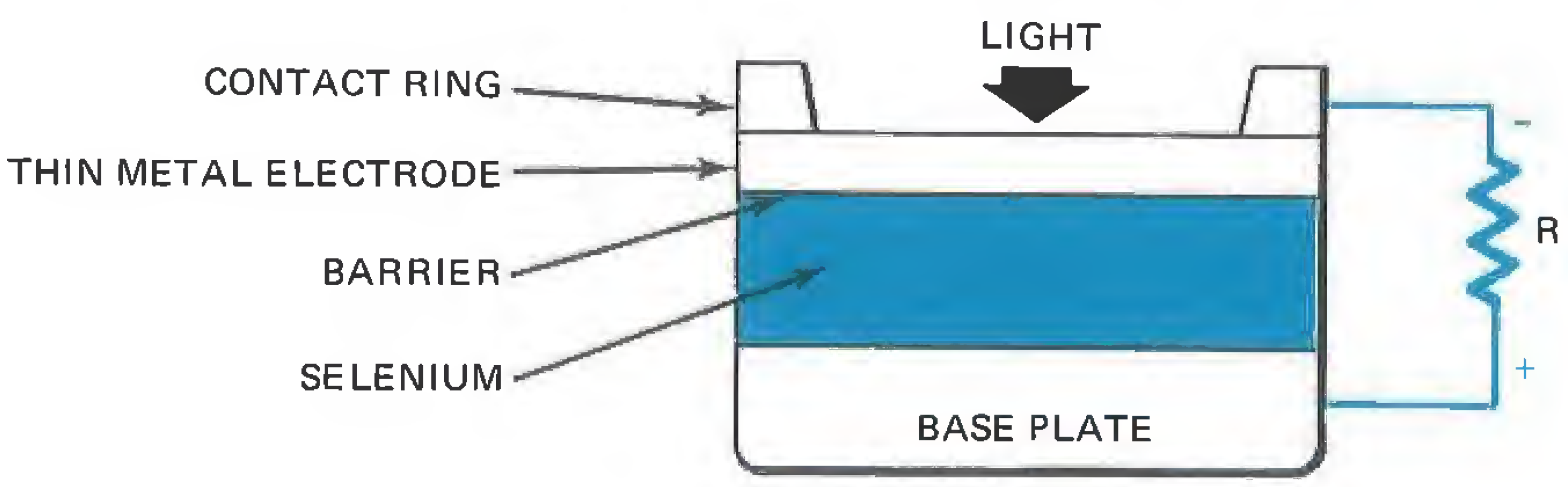


Fig. 13-9 Barrier-Layer Cell

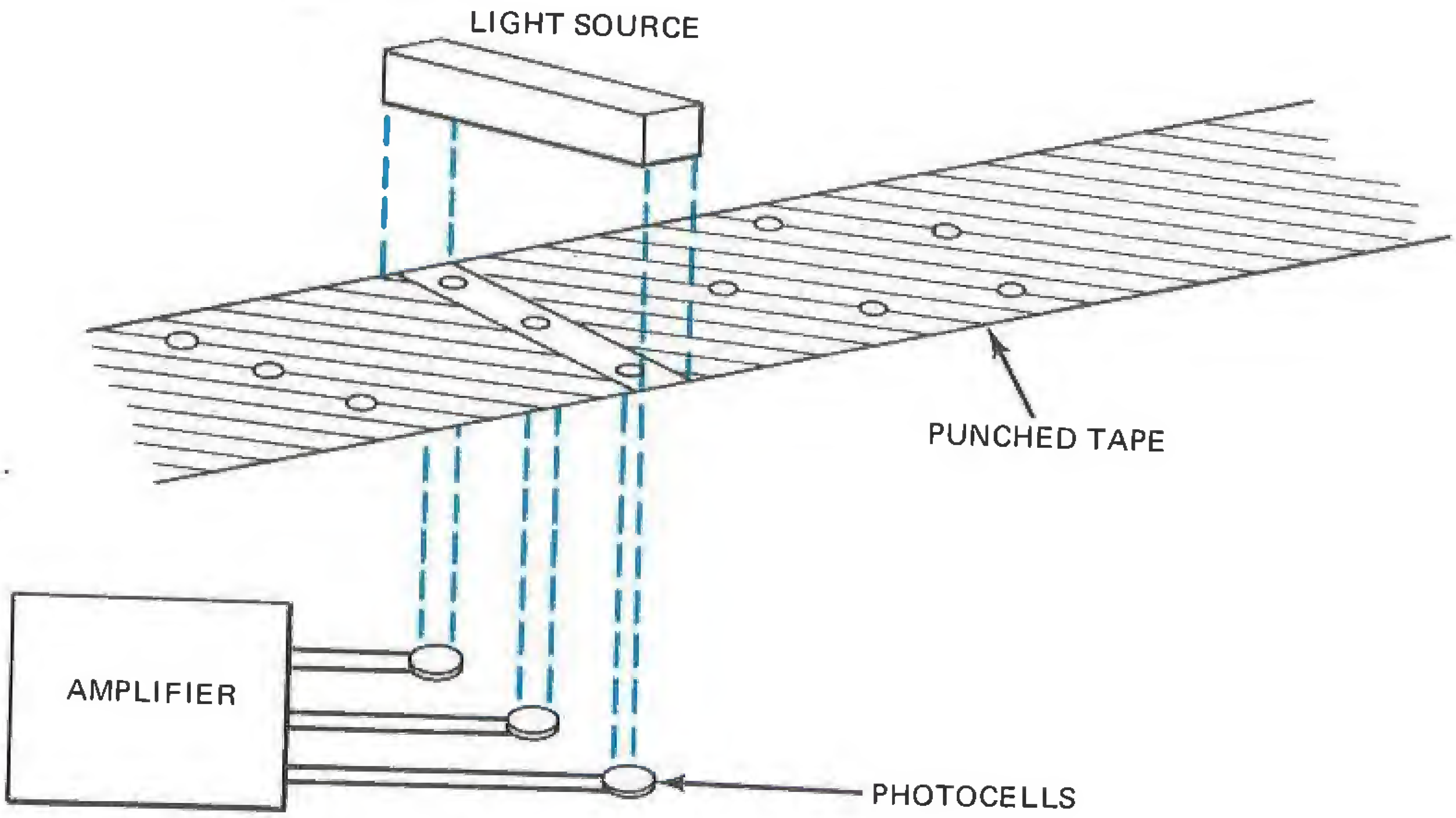


Fig. 13-10 Optical Read-Out of Punched Tape

One application of the photocell is in the reading of information which is on computer tapes. Figure 13-10 shows a simplified version of this device.

A light source of constant illumination is placed above the photovoltaic cells in such a way that a tape can move between the light and the cells. The cells are not energized as long as there are no holes in the tape to allow light through. When a hole passes under the light, the corresponding light energizes the cell and the response is amplified and recorded in the computer network. This arrangement eliminates the need of mechanical readout equipment which is much slower.

Two other applications of this cell are measuring density of material such as water or gas and determining light intensity on photographic equipment. Figure 13-11 shows a simplified schematic of an "electric eye" for a camera.

In the simplified schematic in figure 13-11, the light intensity produces a voltage at the photovoltaic cell. The corresponding voltage produces a current that activates a solenoid which positions a lens cover across the camera lens. The voltage output would have to be calibrated to position the lens cover so that a certain lens opening would correspond to a certain light intensity.

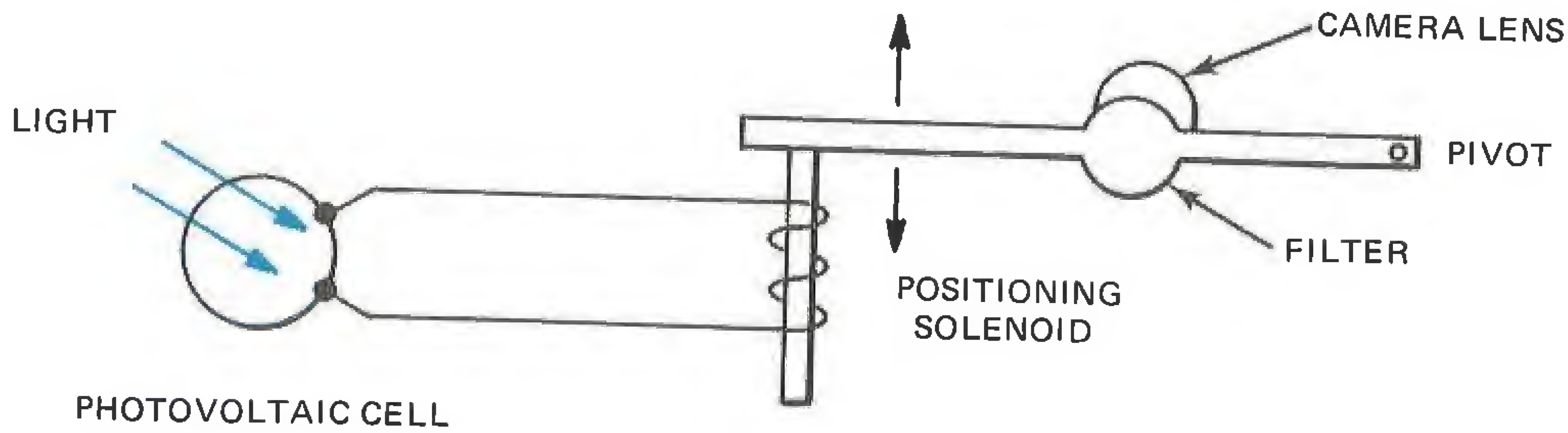


Fig. 13-11 Simplified Electric Eye on a Camera

MATERIALS

1 VOM or FEM
2 Photovoltaic cells (International Rectifier B20 PL or equivalent)
1 Photoconductive cell (International Rectifier CS 120-M6 or equivalent)
1 Transistor, 2N398A
1 DC power supply (0–40V)
2 Light bulbs and sockets, 75W to 100W
1 Variable Transformer
1 Relay (Babcock AK207-2, 300Ω, 10A or equivalent
1 Yard stick
1 Relay counter

PROCEDURE

1. Connect the circuit shown in figure 13-12.

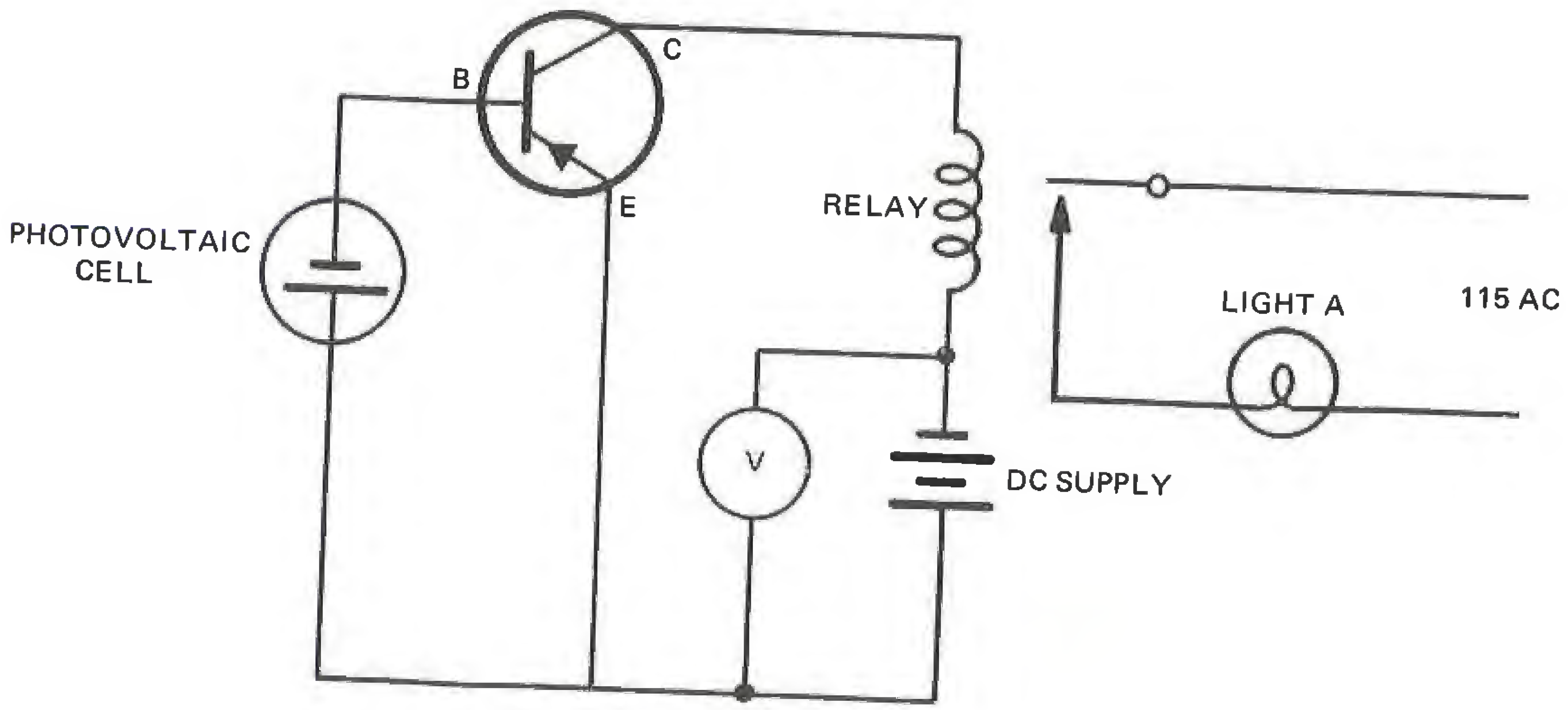


Fig. 13-12 Experimental Circuit

2. Adjust the variable transformer until light A glows faintly when the relay is closed.
3. Connect light B to the 115 VAC source.
4. Place light B six inches away from the photocell so that the face of the cell is fully illuminated as shown in figure 13-13.

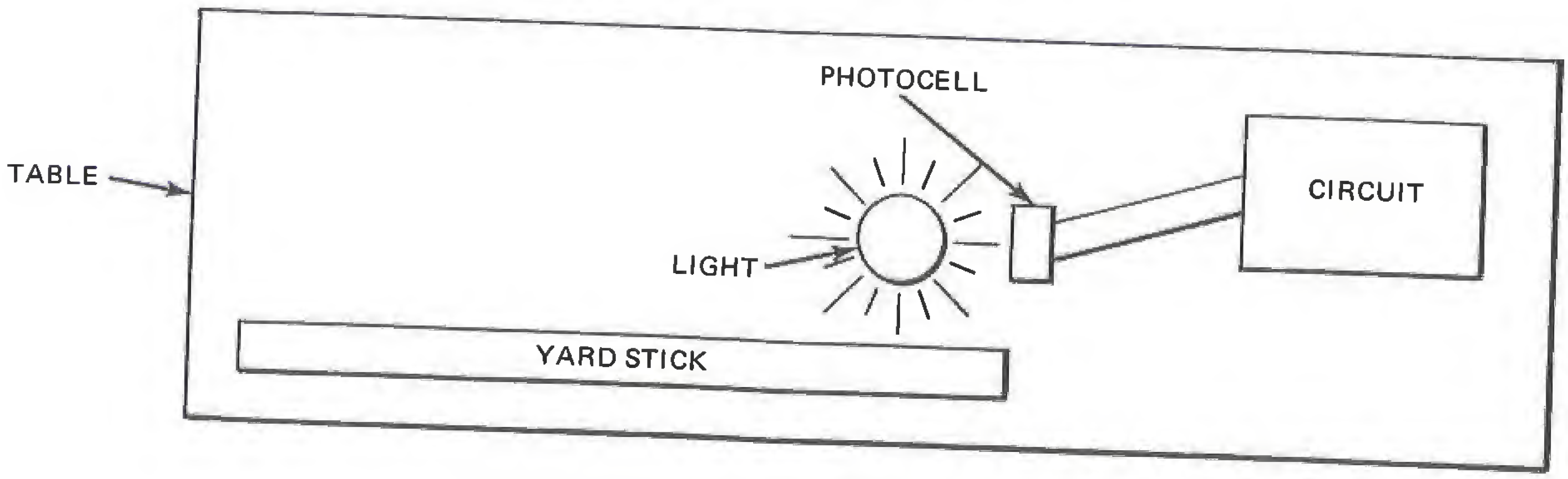


Fig. 13-13 Top View of Experiment

5. Increase the DC supply voltage until the relay closes. Record the voltage required in figure 13-14. **Note: It is not important whether the relay closes or opens the circuit for light A at this time.**

6. Decrease the voltage until the relay opens.

7. Place light source B nine inches away from the photocell.

8. Increase the voltage until the relay closes again. Record the voltage required.

9. Repeat steps five and six for distances of 12″, 15″, 18″, 21″ and 24″. Record all voltages in figure 13-14.

Distance to Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-14 Data Table for Photovoltaic Cell Circuit

10. Place a photoconductive cell in series with the photovoltaic cell.

11. Cover the photoconductive cell so that no light illuminates it.

12. With the light B at six inches, increase the voltage as in step five. Do not exceed 40 volts. Did the relay close?

13. Place the photoconductive cell in such a way that it receives the same amount of light as the photovoltaic cell.

Distance from Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-15 Data Table for Photovoltaic-Photoconductive Cell Circuit

14. Repeat steps 5 - 9 for this arrangement. Record the voltage in figure 13-15.

15. Replace the photoconductive cell with another photovoltaic cell.

Distance from Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-16 Data Table for Two Photovoltaic Cells in Series

16. Repeat the experiment for the two photovoltaic cells in series. Record the voltage in figure 13-16.
17. Replace the light bulb A with a relay counter. **Note: Replace the AC supply with a DC supply for the relay counter.**
18. By moving your hands in front of the photocell, experiment with the distance to the light source and the voltage needed to make the counter work correctly.

    Distance ____________________

    Voltage ____________________

ANALYSIS GUIDE. Plot the voltage versus the light distance for each experiment set-up. It should be apparent how the light intensity affects the circuit voltage needed. Explain why the circuit did not close the relay when the photoconductor was held in the dark. Why were the voltages higher when the photoconductor was in series with the photovoltaic cell?

PROBLEMS

1. Determine the threshold frequency when the energy of the work function of a material is equal to three electron volts.
2. The photoelectric threshold frequency of tungsten is 2300Å. With what energy are electrons emitted from the surface when it is irradiated with ultraviolet light of frequency 6×10^{14} Hertz?
3. Give an application of the circuit in figure 13-12. Explain how the circuit would work and why it would be more efficient than using a mechanical apparatus.

experiment 14 CHEMICAL TRANSDUCERS

INTRODUCTION. The chemical transducer, like many other types of transducers, has found its way into industry with much demand. Even though there have been chemical transducers around for years, they have not often been looked upon as such. In this experiment we will look at the operation involved in converting chemical energy to electrical energy.

DISCUSSION. The term transducer, as defined and applied to instrumentation, denotes that a magnitude of some input value is converted to some other measurable output. The energy input and output may be of any form.

The chemical transducer is one of many transducers currently used in the instrumentation industry. Within the category of chemical transducers, there are a number of different types which depend upon application, and which respond to input-output characteristics.

One of the simplest chemical transducers that can be built is made from a lemon and pieces of zinc and copper foil. The lemon contains citric acid which serves as the electrolyte (a substance in which the conduction of electricity is accompanied by chemical decomposition). The lemon must first be rolled vigorously to break down some of the cell walls. Then two slots are made at extreme ends into which the metal strips are inserted. These metal strips are the electrodes. If a voltmeter were placed in the circuit, a voltage of approximately 0.7 volts would be observed.

Another simple chemical transducer can be made using a beaker of hydrochloric acid. Figure 14-1 shows the basic transducer. The electrodes used are zinc and copper strips.

It is accepted that electric current is related to the flow of electrons. The source of these electrons and how they happen to be released in a chemical transducer will now be examined. The source of electrons can best be observed when a strip of zinc is placed in a solution of hydrochloric acid. When hydrogen combines with chlorine to form hydrochloric acid, the hydrogen becomes deficient of an electron and thus becomes positively charged. The chlorine correspondingly becomes negatively charged as it borrows an electron from the hydrogen atom.

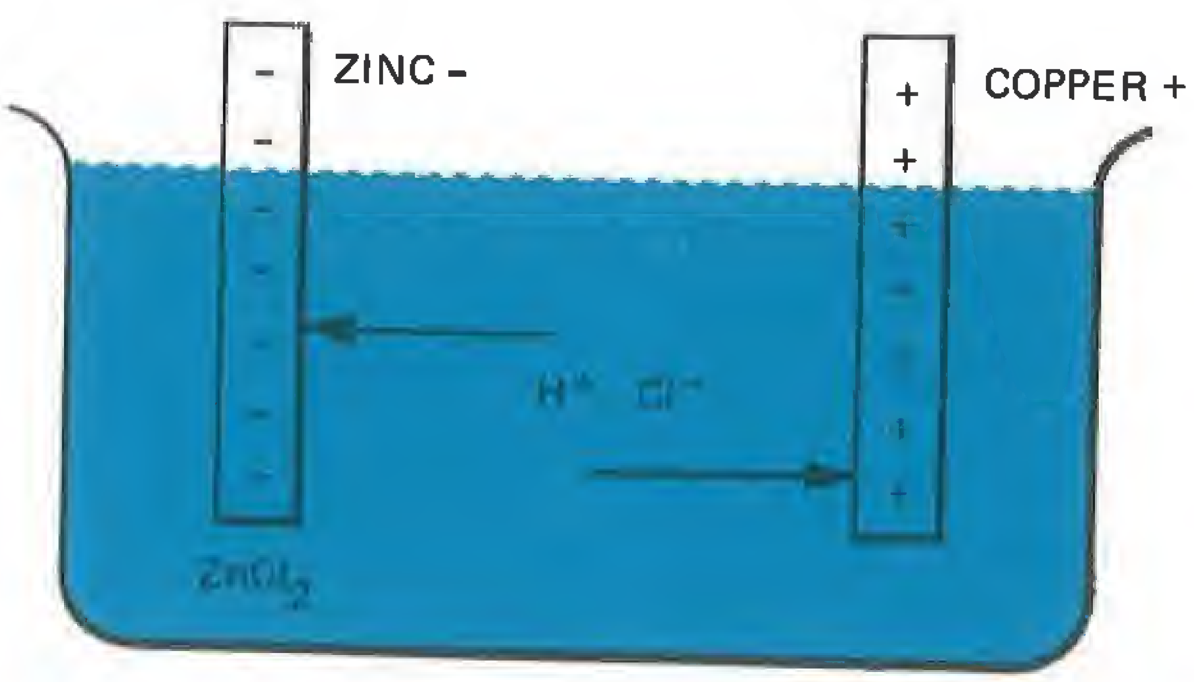


Fig. 14-1 Basic Zinc-Copper Transducer

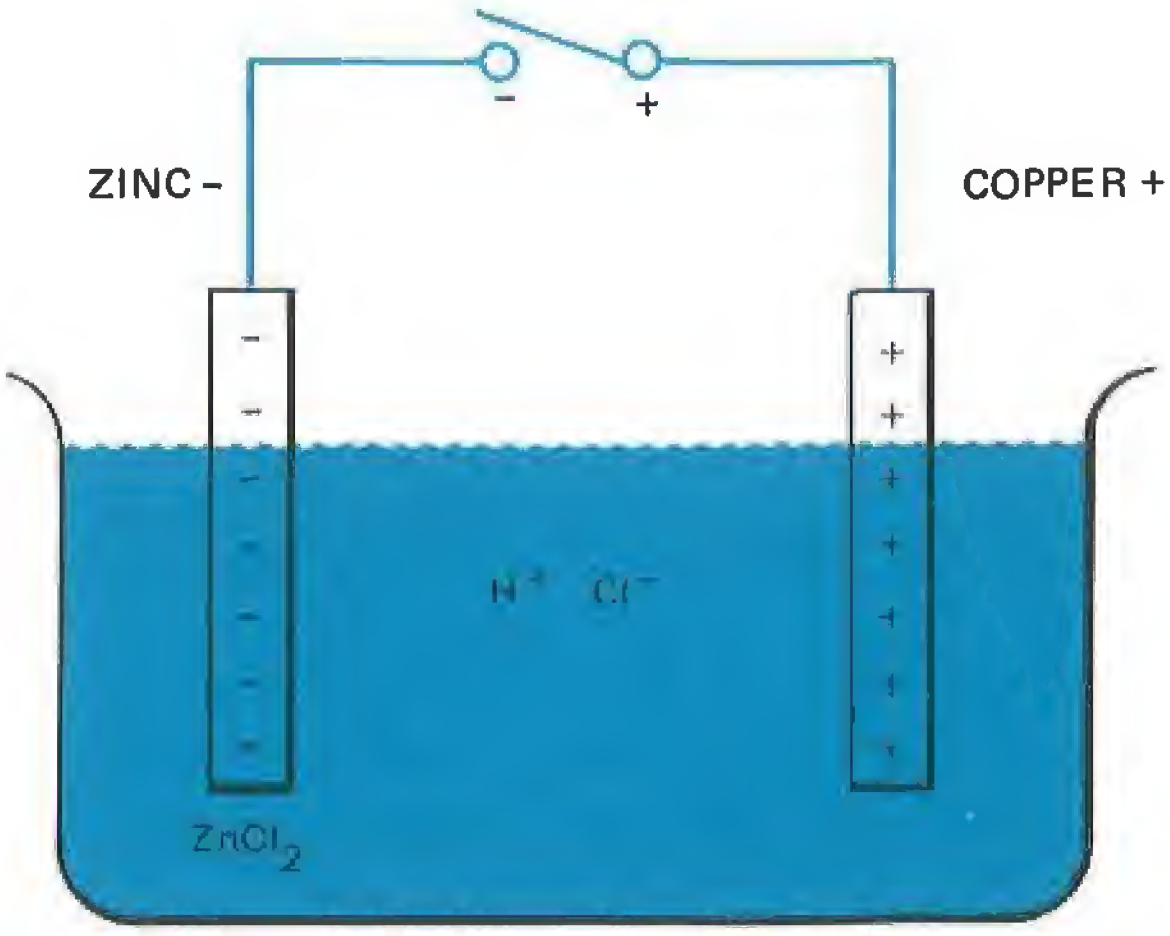


Fig. 14-2 Producing an Electric Potential

The chlorine in the acid in figure 14-1 will combine with the zinc atoms of the zinc electrode to form zinc chloride ($ZnCl_2$). The electron that the chlorine borrowed from the hydrogen is deposited on the zinc rod, creating a negative charge on the rod. As the chloride ion loses its electrons, the hydrogen ion, which loaned its electron originally, can go in search of a source of free electrons to re-establish its original atomic structure. Since the copper rod is such a source, the hydrogen ion takes an electron from the copper atom creating a positive charge on the copper rod. For each electron built up on the zinc rod, an electron is removed from the copper rod.

If a conductor is placed across the electrodes with a switch as shown in figure 14-2, the chemical action proceeds until sufficient potential difference is established that the negatively-charged chlorine ions do not have sufficient chemical attraction to reach the zinc. The formulation of zinc chloride will then cease.

When the switch is closed, the free electrons will flow through the conductor because the electrons are attracted by the positive charge of the copper rod. The current flow will attempt to return the potential difference to zero, but as the flow begins, chemical action again starts depositing electrons on the zinc rod and removing them from the copper rod. A steady flow of electrons is produced in one direction around the loop. This flow is known as direct current.

The device talked about in the preceeding paragraphs is commonly known as a battery. It can also be classified as a generator or a transducer. The word battery originally referred to a group of chemical cells, but the cell in figure 14-2 can be considered a single cell battery.

As long as the switch is closed in figure 14-2, energy is taken from a chemical form and conveyed by the electric current into energy that could be used to run a light bulb or motor. During the energy transfer, the chlorine ions combining with the zinc dilutes the acid and eats away the zinc rod. If this continues, the battery will no longer produce voltage after a certain length of time. To offset this problem, the chlorine can be separated from the zinc by connecting an electric generator to the battery which raises

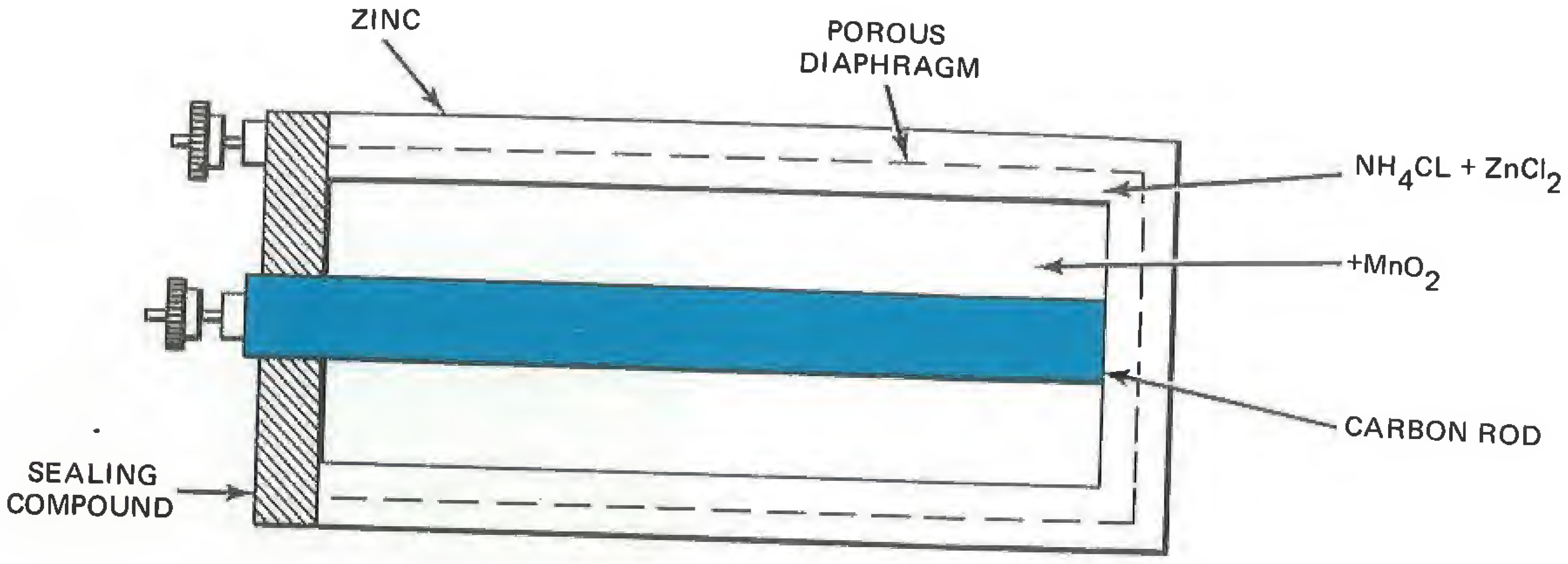


Fig. 14-3 Transducer Cut-Away (Dry Cell)

the potential difference above the level that stops the chlorine ions from reaching the zinc atoms. This process is known as recharging the battery and it is at the expense of the electrical energy of the generator.

Sometimes it is more practical to replace the used acid and zinc rod than it is to recharge the battery. In such a case the battery is known as a primary cell. A secondary cell is one in which the cell can be recharged by converting the outside electric energy into energy stored inside the chemical cell. A familiar battery of this sort is the lead-cell battery used in the automobile. Since it can be recharged, it is sometimes called a storage battery.

A common primary cell is the flashlight battery, often referred to as a "dry cell." As mentioned above, a primary cell is usually discarded instead of recharged due to the expense involved. However, the more expensive dry cells manufactured today can be recharged to some extent and their life can be prolonged by using dry cell battery chargers which have recently become available to the consumer. Contrary to its name, the "dry cell" is not a dry cell; rather it has a solution of ammonium chloride as an electrolyte. However, most of the electrolyte is absorbed by the contents of the cell giving the material only a moist appearance.

Today, whenever it is necessary to obtain small amounts of electric current, the dry cell is usually employed. Unlike the wet cell, the dry cell may be used in any position since there is no liquid to spill. There is, of course, no evaporation of liquid, and the element of danger involved in handling acid has been all but eliminated. Figure 14-3 shows a cutaway view of a dry cell. This type of cell, as ordinarily constructed, consists of a zinc can containing ammonium chloride and zinc chloride which is made dry by absorbing it into a porous material such as sawdust. At the center is a carbon electrode surrounded by manganese dioxide, MnO_2. Although the chemical action is not quite so simple as that of a metal-acid wet cell, such as in figures 14-1 and 14-2, the net results are the same. Surplus electrons are added to the zinc can by the electrolyte giving the can a negative charge, and the hydrogen ions rob the carbon rod of electrons giving the carbon a positive charge. Hydrogen bubbles try to form on the positive electrode creating a polarizing effect. This essentially acts as an insulator and to offset it, the majority of the dry cell is packed with manganese dioxide which functions as a depolarizer. The manganese dioxide combines

with the hydrogen as it is released, preventing polarization from taking place. Since hydrogen gas is not given off, the container can be completely sealed to make the dry cell completely portable.

The carbon-zinc dry cell produces 1.5 volts per cell and a series combination can be made that will produce any needed amount of voltage. The carbon-zinc dry cell does have some disadvantages. Local chemical action can take place within the cell even though the external circuit is disconnected. Therefore, the shelf-life of such cells is limited. An improvement to this battery is the magnesium-alkaline cell. It can maintain its terminal emf at a given current drain for more than twice as long as a carbon-zinc cell of the same size.

If it were not for the polarization effect which the carbon-zinc battery produces, the battery could be made smaller in size, because there would not be space required for the manganese dioxide.

A cell which is produced that does not need the space for depolarization chemicals is the mercury cell. It can be made fairly small but it is more expensive than the carbon-zinc cell. Zinc forms the positive electrode and mercuric oxide and graphite form the negative electrode. The electrolyte is potassium hydroxide. Because of its size, it is used primarily in hearing aids.

The magnesium-alkaline cell and the mercury cell are both primary cells. The emf produced by the manganese-alkaline cell is 1.5 volts and that of the mercury cell is 1.3 volts.

The storage battery commonly found in the automobile is an example of a secondary source. Figure 14-4 gives a schematic of a simple lead-acid cell.

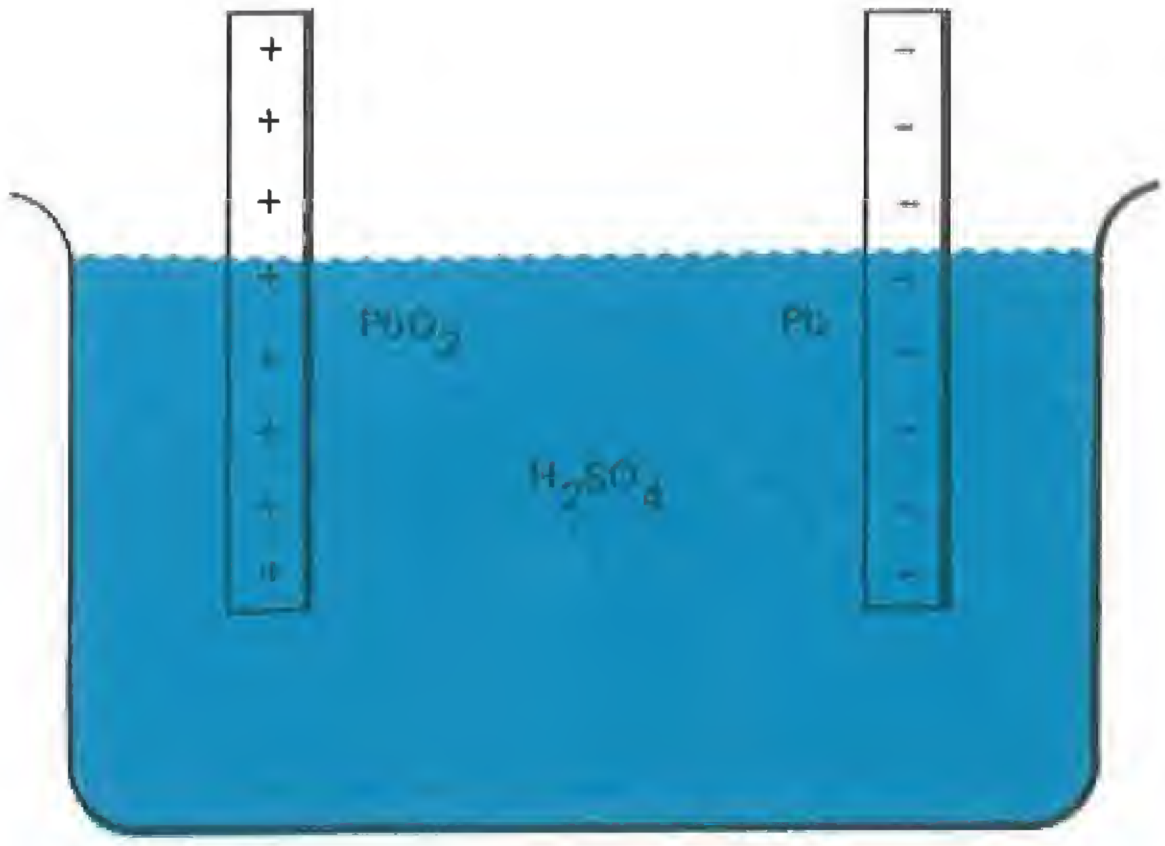


Fig. 14-4 The Lead-Acid Storage Battery

The positive electrode is made of lead oxide, PbO_2. The negative electrode is pure lead. The electrolyte is sulfuric acid, H_2SO_4, which separates into H^+ and SO_4^{--} (sulfate) ions. When electrons leave the lead electrode, the lead Pb^{++} ions in the electrolyte combine to form lead sulfate. The chemical equation is

$$Pb + SO_4^{--} \rightarrow PbSO_4 + 2e^- \qquad \textbf{(14.1)}$$

At the positive electrode, lead dioxide, hydrogen ions, sulfate ions, and incoming electrons combine to form lead sulfate and water.

$$PbO_2 + SO_4^{--} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O \qquad \textbf{(14.2)}$$

The effect of drawing current from the battery is the depositing of lead sulfate on both sets of plates. When no more lead or lead oxide is accessible to the electrolyte, the battery is "dead" and can produce no more current. Since the lead-acid battery is a secondary source, it can be recharged. To recharge it, a current is passed through it in the opposite direction from the car generator or alternator, which reverses the above reactions and restores the plates to approximately their original composition. The battery will continue to function until the plates become completely erroded with sulfate and can no longer take part in the reaction.

The emf of a charged lead-acid storage cell is 2.1 volts. Therefore, for 12 volts used in the car, six such cells are connected in series.

In any electrolyte in a chemical transducer, there is a resistance to the movement of the ions as they carry the current from one electrode to the other. This resistance is called the internal resistance of the transducer. One of the major advantages of the lead-acid battery is its low internal resistance which permits currents of several hundred amperes to be drawn for short periods of time. The internal resistance increases at low temperature because the ions move much slower in a cold electrolyte. As a result, the current available to start an engine on a cold winter morning may be only half that available on a warm summer day.

Two other types of storage cells are the Edison cell and nickel cadmium cell, both of which have alkaline rather than acid electrolytes. The electrodes of the Edison cell are oxides of nickel and iron and the electrolyte is potassium hydroxide. Edison cells produce 1.25 volts, are lighter and more rugged and have longer lives than lead-acid cells. The disadvantages are the high cost and the high internal resistance, 10 times that of lead-acid cells.

Nickel-cadmium batteries have electrodes of nickel and cadmium compounds in an electrolyte of potassium hydroxide. This battery has good low-temperature performance but is expensive. A nickel-cadmium battery may retain 50% of its initial charge after a year in storage, while a lead-acid battery loses about 1% of its charge per day while in storage.

A fuel cell is another chemical-electrical transducer. This particular transducer has a continuous flow of reactant chemicals. Because of this, the cell never becomes exhausted (like the dry cell) and never needs recharging (like the storage cell). Fuel cells are used in space vehicles to supply electrical energy to the space craft. Their high power/weight ratio is very advantageous, and they are being developed as power sources for electric cars and as self-contained units to furnish electricity to homes. One such cell is the hydrogen-oxygen cell illustrated in figure 14-5.

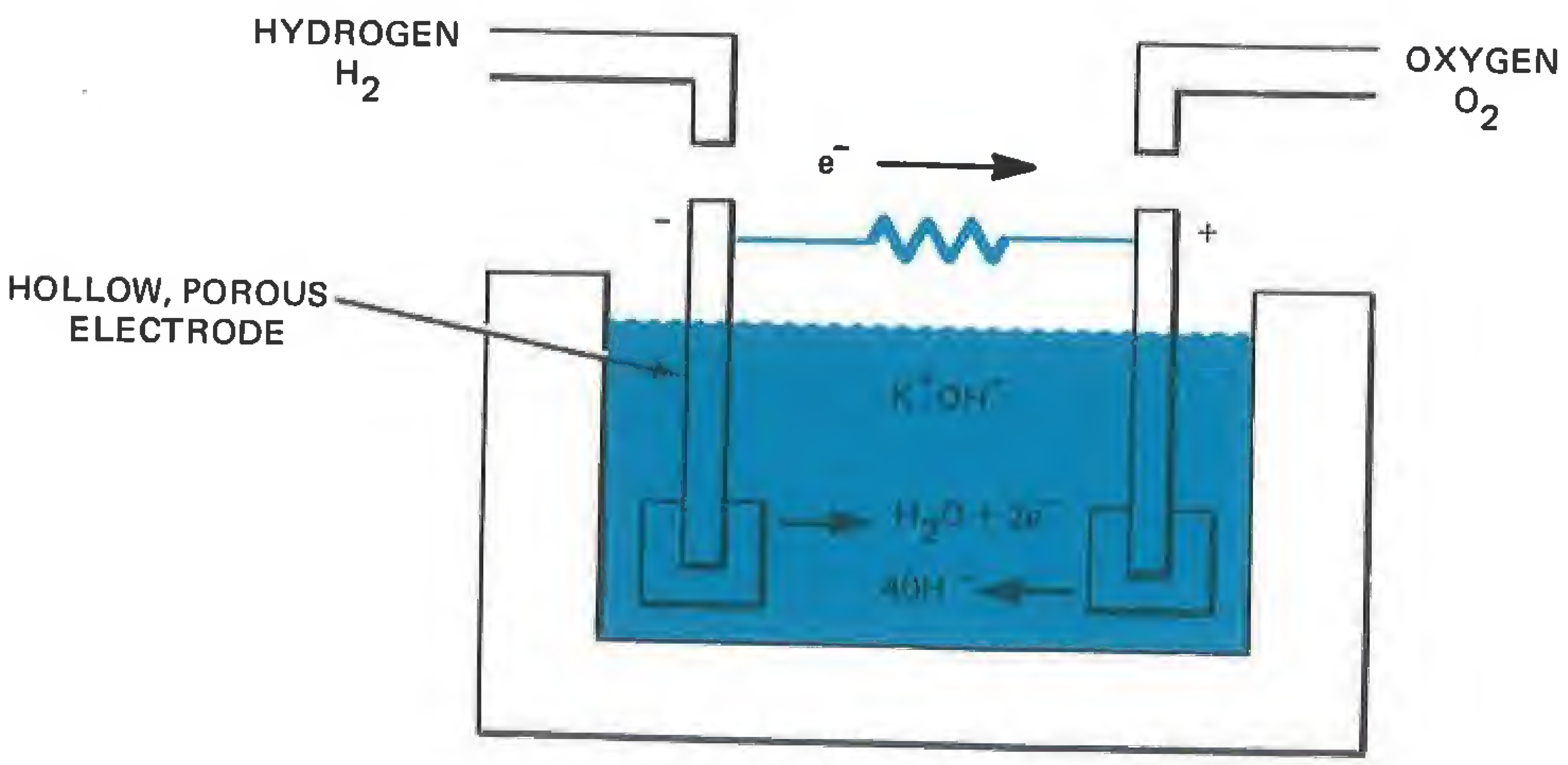


Fig. 14-5 A Hydrogen-Oxygen Fuel Cell

The hollow electrodes are made of inert conducting materials with microscopic pores that permit the gases to come into contact with the electrolyte at a slow rate. The electrolyte is a potassium hydroxide (KOH) sosution that contains K^+ and OH^- ions. The chemical reaction at the negative electrode involves the hydrogen molecules combining with the hydroxide ions to form water while releasing electrons. The chemical equation is

$$\boxed{H_2 + 2OH^- \rightarrow 2H_2O + 2e^-} \qquad (14.3)$$

At the positive electrode, the oxygen molecules combine with water molecules and the incoming electrons from the other electrode to produce hydroxide ions.

$$\boxed{O_2 + 2H_2O + 4e^- \rightarrow 4OH^-} \qquad (14.4)$$

The reaction in 14.3 must occur twice for each time that reaction 14.4 occurs. The net effect of both reactions may be summarized as

$$2H_2 + O_2 \text{ — } 2H_2O + \text{flow of 4 electrons}$$

The combination of hydrogen and oxygen in a fuel cell produces water at approximately 10^8 joules of electrical energy. That is enough energy to power a 100-watt light bulb for nearly two weeks. The emf of a hydrogen-oxygen fuel cell is about 0.9 volts.

The voltage of a chemical transducer can be measured, but the measurement of voltage alone is not always an accurate indication of the condition of the transducer. A measurement of the actual voltage produced while the transducer is under a load is a much better indication. If the internal resistance is high, the output voltage will be very low, indicating a weak cell.

MATERIALS

- 1 Resistor 1kΩ
- 2 Beakers
- 2 Copper rods
- 2 Zinc rods
- 1 Container of distilled water
- 1 Pint sal ammoniac (ammonium chloride)
- 1 VOM or FEM

PROCEDURE

1. Prepare a solution of sal ammoniac, one part of sal ammoniac in four or five parts of distilled water, and dissolve.
2. Fill the beaker about half full.
3. Place the zinc rod in the solution.
4. Observe the surfaces of the rod and note any action.
5. Place the copper rod in the solution.
6. Observe the surface of the rod and note any action.
7. Place the voltmeter across the terminals and record the open circuit voltage of the cell.

____

8. Place a 1k resistor in series with the terminals. Record the voltage across the load. ______

9. Determine the internal resistance of the battery. ______

10. Prepare another battery with the same solution.

11. Repeat steps 3 - 9 for this battery. Open circuit voltage ______ Load voltage ______ Internal resistance ______

12. Place the two cells in series.

13. Determine the output voltage of the series combination. Series voltage ______

14. With the 1k resistor across both cells, determine the load voltage. ______

15. Determine the internal resistance of the series combination. ______

16. Double the solution in each cell.

17. Determine the internal resistance of this series combination. ______

ANALYSIS GUIDE. Describe the action of the solution as the electrodes were placed in it. Were the internal resistances of the cells equal? Explain. Did the sum of the internal resistances equal the internal resistance of the series combination? Why or why not? Did the internal resistance of the cells change when the solution was doubled?

PROBLEMS

1. Draw a schematic of four chemical transducers connected in series showing all polarity markings. Figure the output voltage of the circuit, given a value of 1-1/2 volts per transducer. With an internal resistance of 1-1/2 ohms per cell, determine the current when the series cells are across a 10Ω load.

2. Draw a schematic of four transducers connected in parallel showing all polarity markings. Show the voltage and current outputs given a value of 1-1/2 volts per transducer, and an internal resistance value of 1-1/2 ohms each. Use a load of 10 ohms.

3. From the above two problems, what can be said about series and parallel batteries as to current and voltage?

experiment 15 SOUND TRANSDUCERS

INTRODUCTION. Sound transducers have been used for years and some are commonly referred to as microphones. There are several different types of sound transducers available, each showing its own characteristics. In this experiment we will examine the basic operation of a sound transducer.

DISCUSSION. As the string, shown in figure 15-1, moves to the right, it compresses the air directly in front of it. The force of the string as it moves to the right causes the small volume of air through which it passes to be compressed.

When the string completes its motion to the right, it reverses direction. As the string moves to the left, the pressure is taken off of the air immediately to the right, thus allowing it to expand. This is shown in figure 15-1B. As the string moves further to the left, the relaxation of the pressure on the air is transmitted outward through successive masses of air.

Each time the string makes one complete movement forward and back the air is compressed and then relaxed as it moves outward from the string. One expansion and one compression make up a complete cycle. The number of cycles produced per second is equal to the frequency of vibration of the string. A number of cycles might look like figure 15-2.

You may have noticed that a loud sound, such as a gun blast or the blare of a loud speaker, can set objects in a room vibrating. The sound is moving across the room and setting the bodies in motion by transmitting energy to them. This behavior is characteristic of wave motion. It illustrates that sound is transmitted through air as a wave. As the sound wave moves through the room, it causes all the particles in its path to vibrate at the same frequency as the transmitted wave.

The sound waves produced by a violin string produce waves by the vibration of the string as was shown in figure 15-1. The sounds coming from a radio speaker are pro-

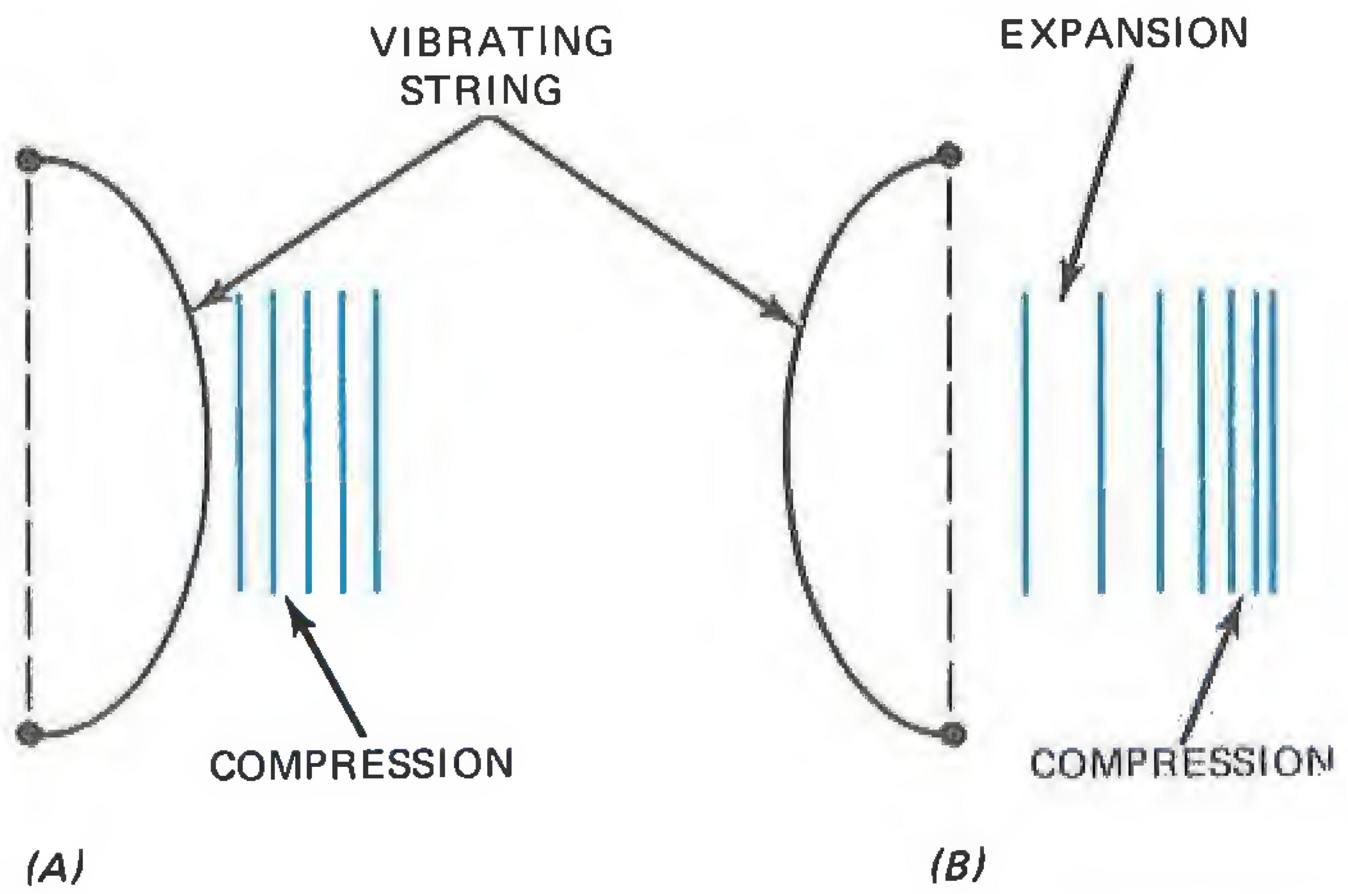


Fig. 15-1 Sound Production by a Vibrating String

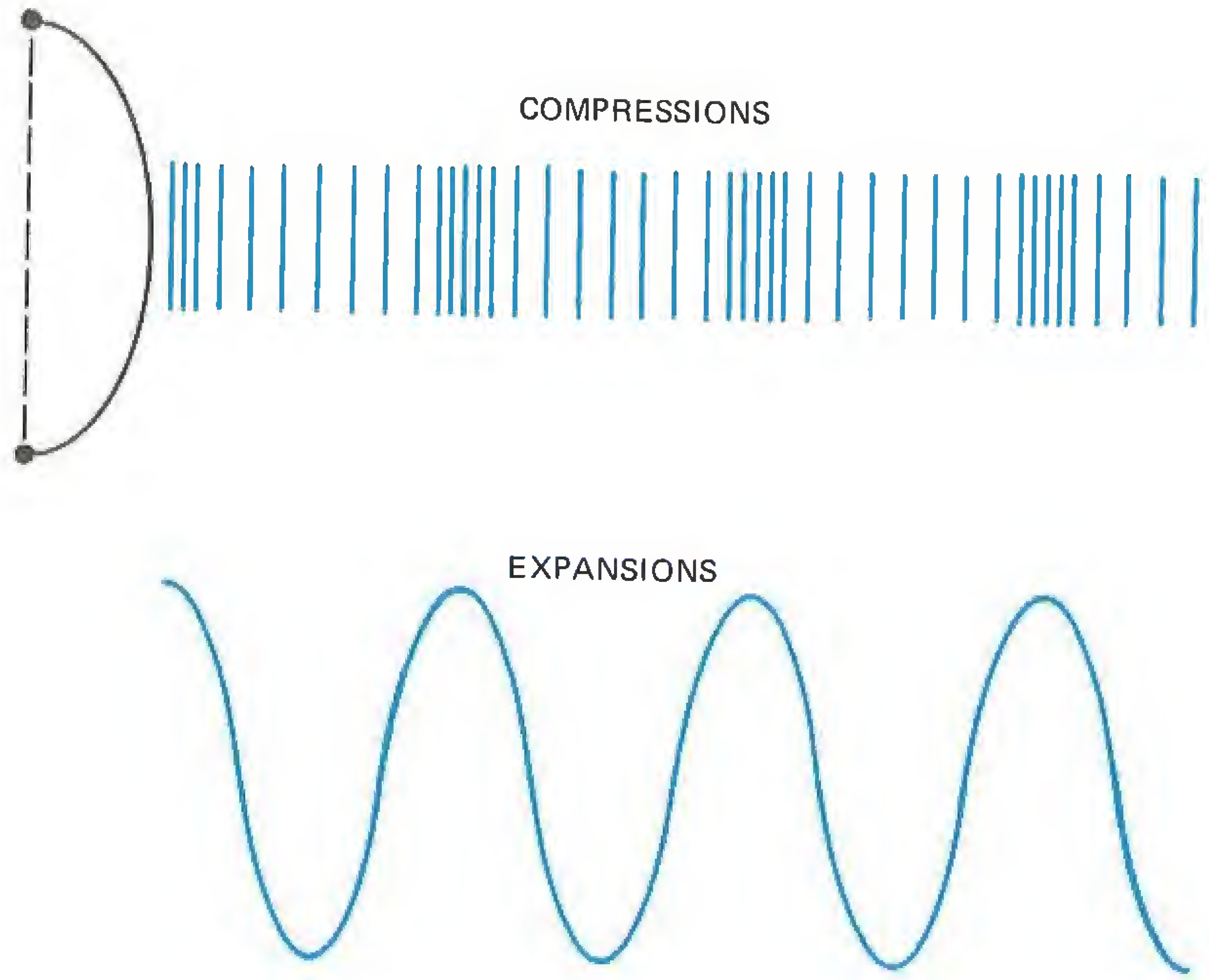


Fig. 15-2 A Number of Cycles of a Vibrating String

duced by a vibrating cone. The sound of the human voice is made by the vibration of the vocal cords.

Sound waves are transmitted in much the same way as water waves. The cross section of a water wave is analogous to the sinusoidal wave produced by the vibrating string shown in figure 15-2.

The exact procedure by which the ear detects sounds and transmits them to the brain is beyond the scope of this discussion. But, in short, the passage of sound waves over the ear causes the ear drum to vibrate which sends impulses to the brain. A sound transducer acts in much the same way as does the human ear.

The sound produced by a source can be converted into electrical impulses and amplified. A pressure-to-voltage transducer for operation in air is known as a microphone. Transducers for detecting sound in solid bodies are vibration pick-ups. This is what is used in phonograph cartridges to pick up the sound from a phonograph record and transmit it to an audio amplifier. One voltage-to-pressure transducer for operation in air is known as a speaker. Both the microphone and the phonograph pick-up use a speaker to transmit the amplified electrical signals they produce and create an audible sound.

A microphone is needed to convert tiny acoustic vibrations into electrical waves. Each microphone has two basic actions: (1) converting acoustical vibrations of the air into mechanical vibrations by the process of moving a diaphragm, and (2) converting the movement of the diaphragm into an electrical current or voltage.

It is not the purpose here to develop the theory of microphone design or operation, which is rather a specialized field in itself. However, it seems worthwhile to list the main types of microphones that are in relatively common use. These include the carbon, dy-

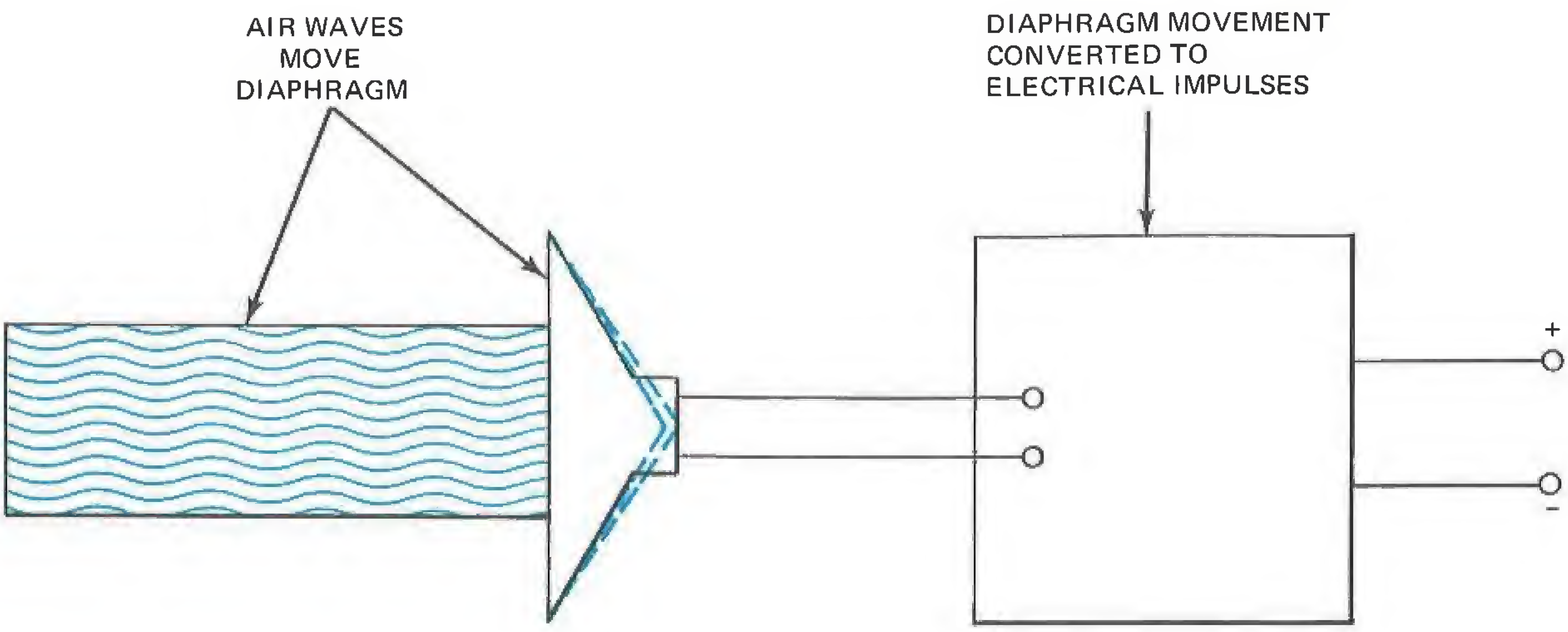


Fig. 15-3 Basic Parts of a Microphone

namic, ribbon, capacitor, and crystal varieties. All of these microphones have the same basic parts shown in figure 15-3.

The carbon microphone was the earliest type. It was invented by Thomas Edison in 1877, and many schoolboys have made simple ones using carbon rods out of old flashlight batteries. It does not give good quality sound as it exhibits both nonlinearity and hysteresis. The carbon granules tend to produce considerable electrical noise. The principle of operation is very simple. Air pressure changes the resistance of the device by packing the carbon granules more or less tightly as the diaphragm moves in and out. The current in the circuit, therefore, fluctuates at the sound frequency. This current is passed through the primary coil of a transformer. The output from the secondary will, therefore, contain no DC component. The most common circuit configuration is shown in figure 15-4.

A dynamic microphone transducer consists of a coil or wire moving in a magnetic field because of the pressure of sound waves

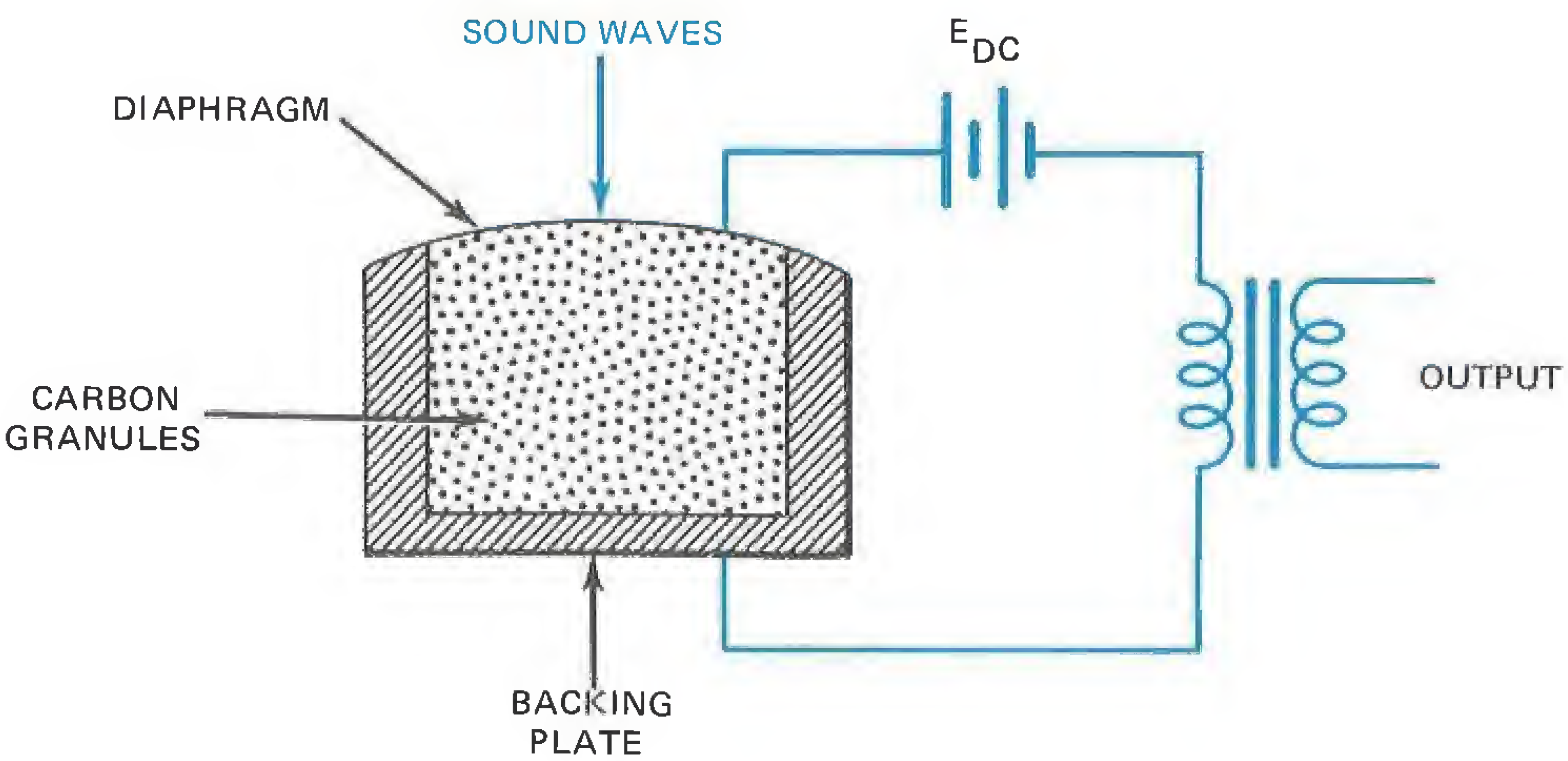


Fig. 15-4 The Carbon Transducer

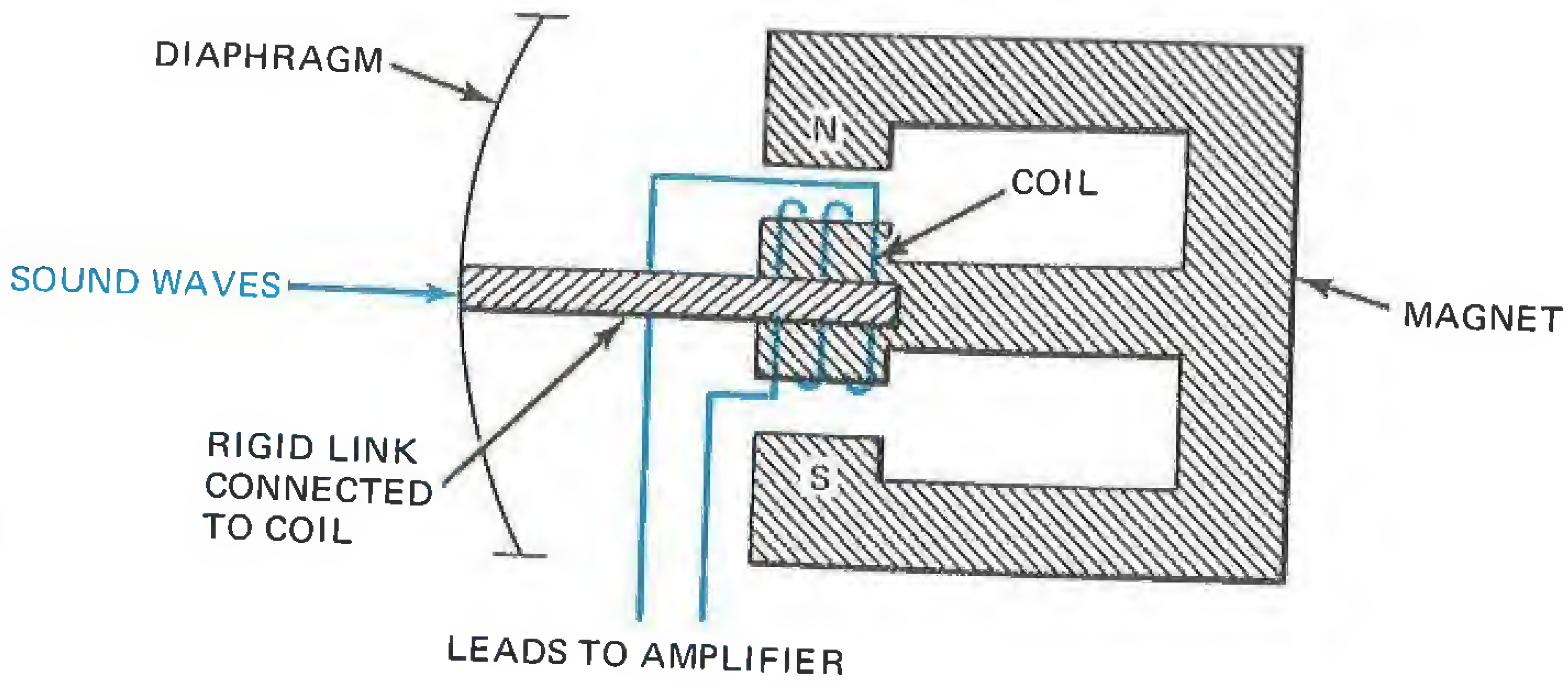


Fig. 15-5 The Dynamic Transducer

striking the diaphragm (figure 15-5). An emf is induced in the moving coil of wire, and this is amplified by a conventional audio amplifier. Because the movement is the essential feature for conversion, a microphone using this principle is often called a dynamic or a moving-coil microphone. The problem in making a microphone of this type is that a large movement is needed to produce even a small current. The movement of the air particles due to sound waves is small. This problem is overcome, to some extent, by increasing the intensity of the magnetic field, bringing north and south poles together, which allows the wire to move in a narrower space.

The ribbon microphone transducer of figure 15-6 is similar in principle to the dynamic transducer. In the ribbon transducer the coil is replaced by a thin aluminum or duraluminum foil. The foil is of the order of an inch in length, about one ten-thousandth of an inch thick, and is usually corrugated. The ribbon is mounted between the poles of a long, narrow magnet and serves as both a diaphragm and moving conductor.

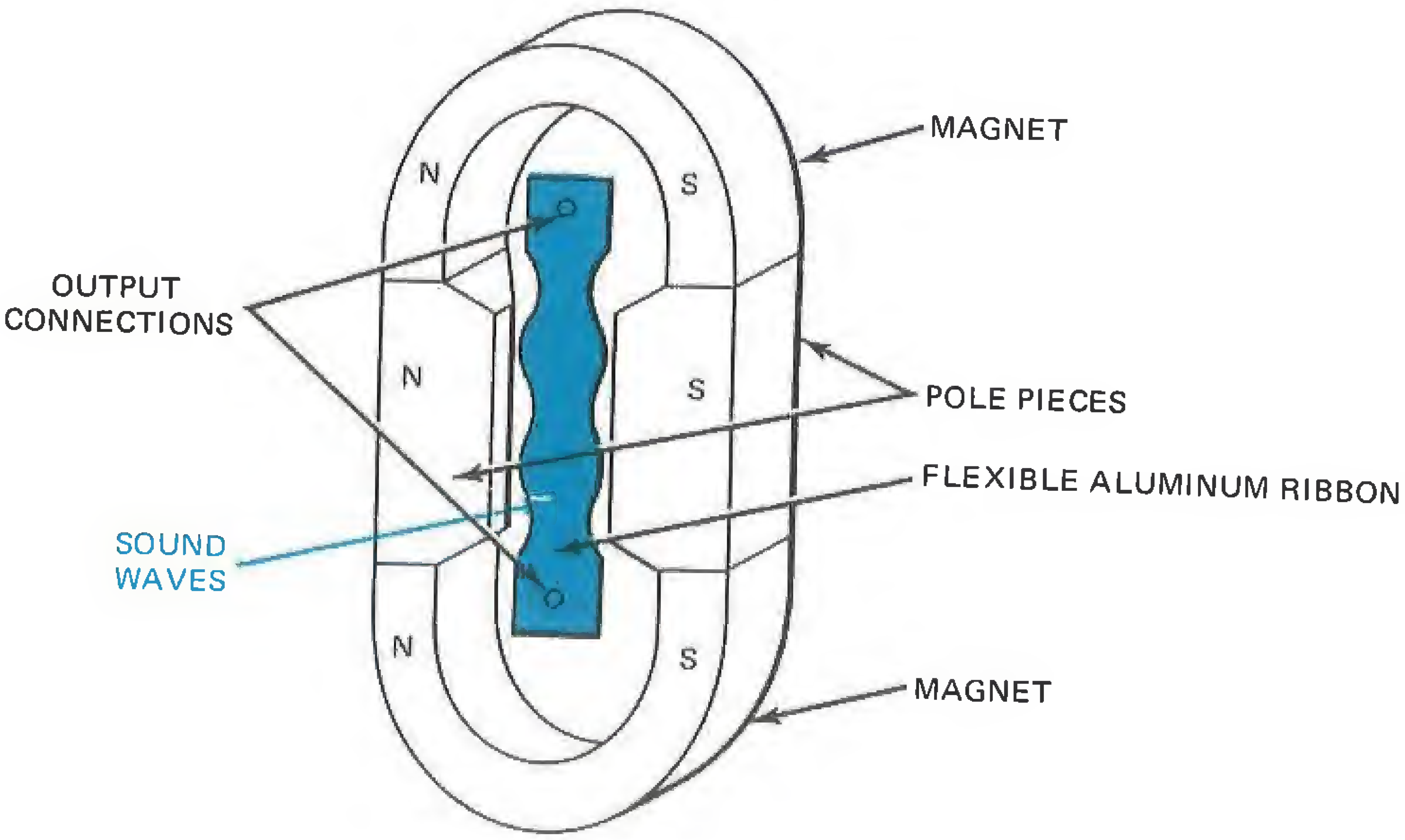


Fig. 15-6 The Ribbon Transducer

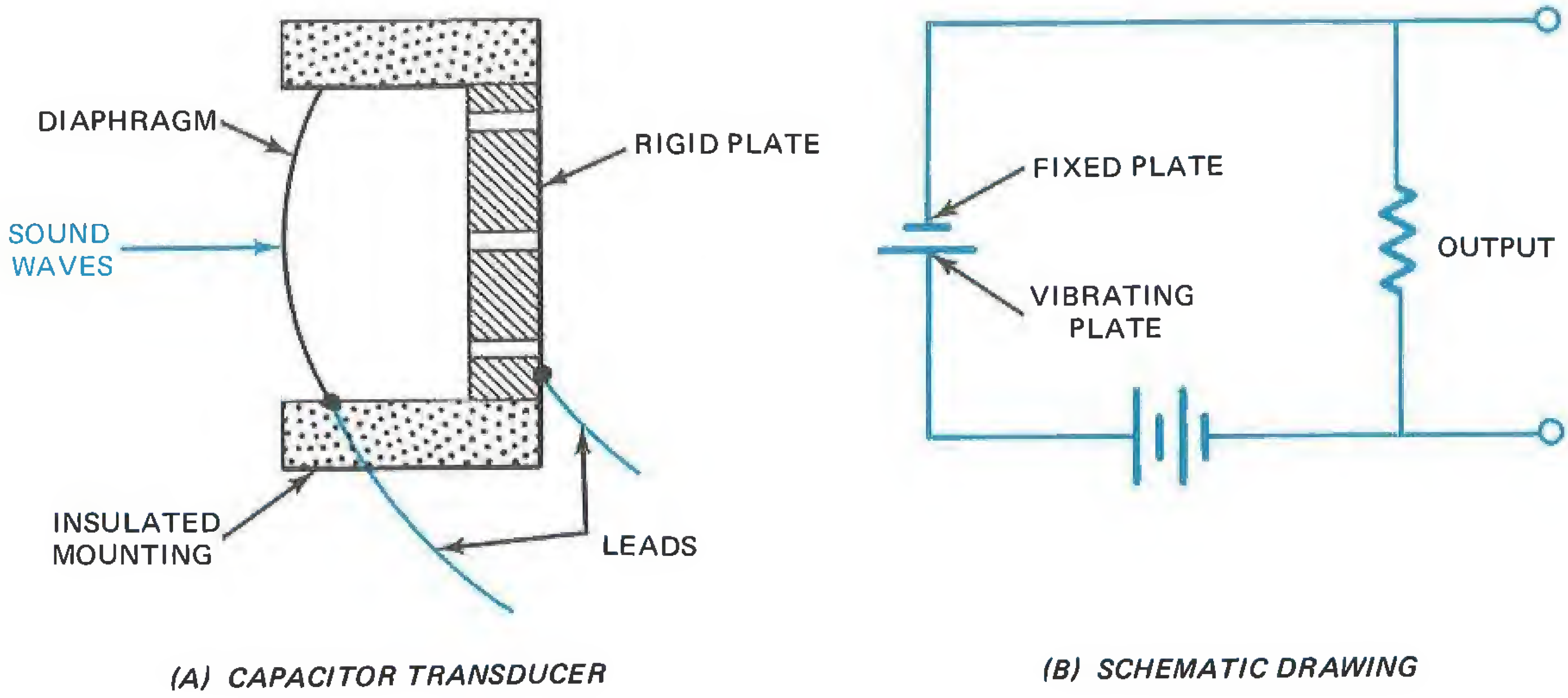


Fig. 15-7 Capacitor Transducer Schematic

Ribbon transducers have an excellent frequency response, but their voltage is small and the source impedance looking back into the transducer is very low, on the order of an ohm. They are rather susceptible to damage and are likely to pick up wind noises if used outdoors. Since both sides of the foil are open to the air, this transducer is also referred to as a velocity type. Its response is proportional to the velocity of motion of the air particles in the sound wave. These transducers are also called pressure-gradient transducers because the movement of the ribbon is due to the pressure difference between its back and front. Hence, either velocity or pressure-gradient is equally descriptive of the action of the ribbon transducer.

The capacitor microphone transducer, figure 15-7A, is the acknowledged queen of the laboratory microphones. It is the accepted standard for precise acoustical measurements. A capacitor transducer always requires a voltage supply for its operation, much like the carbon transducer. In this case, however, a potential difference on the order of 100 volts is required in contrast to the three volts or so used to operate carbon transducers. It operates on the principle that sound waves striking the conducting diaphragm change the capacitance between it and a metal plate mounted close behind. This fixed plate is mounted about 0.001 inch from the diaphragm. The sound wave vibrations are continually flowing onto or away from the plates. These charges flow through a very high resistance, which produces changes in potential. The output is taken across the resistor. The capacitor transducer must operate into as high an impedance as possible. The schematic drawing of the capacitor transducer is shown in figure 15-7B.

The following formula gives the resulting capacity variation that applies to this type of transducer.

$$\boxed{C = 0.0885K\,\frac{(n-1)A}{t}\ \text{(pico-Farads)}} \qquad (15.1)$$

where

A = area of one side of one plate in square inches
n = number of plates
t = thickness of dielectric in centimeters
K = dielectric constant

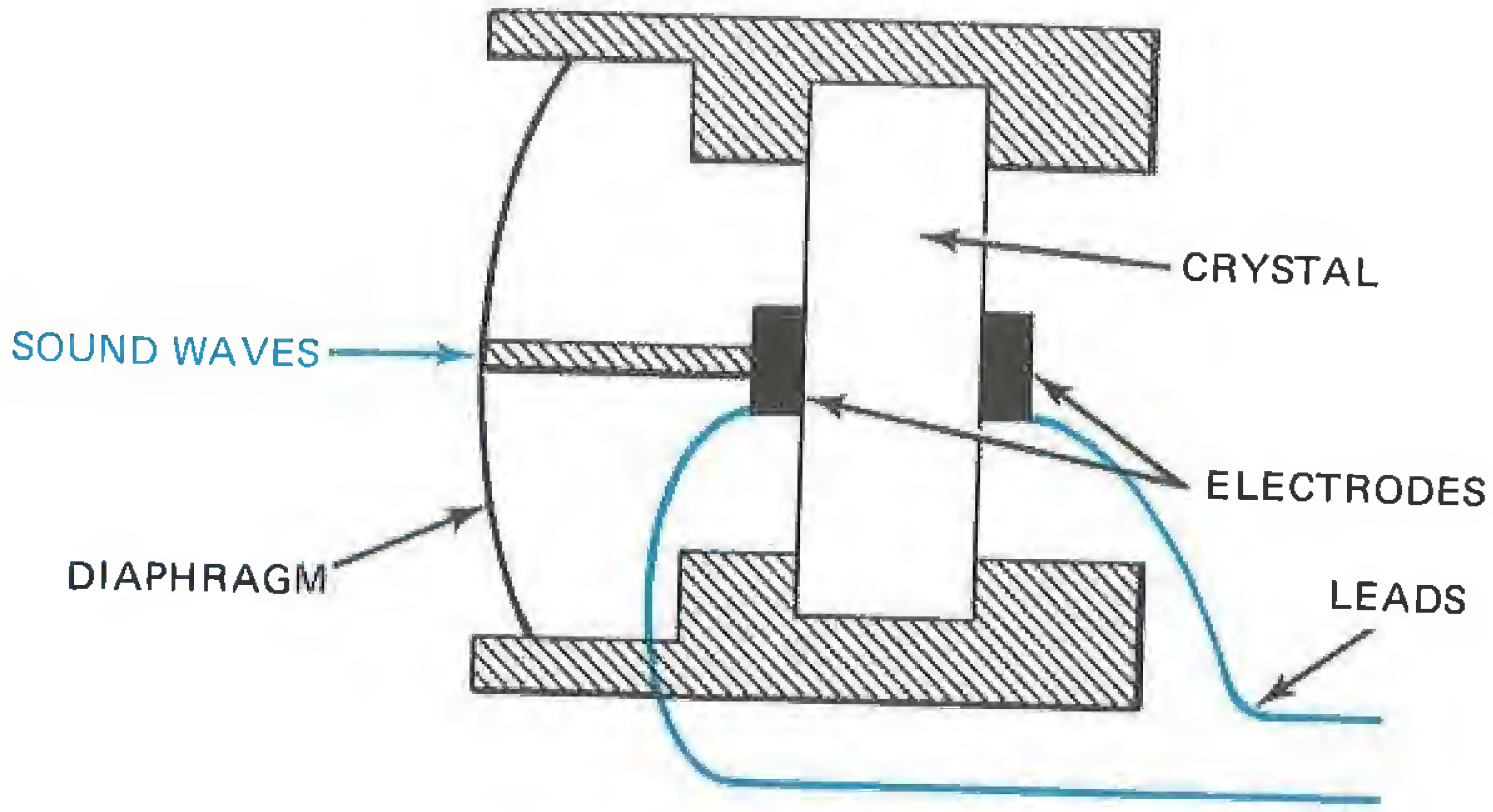


Fig. 15-8 Crystal Transducer

The crystal microphone transducer is second in quality only to the capacitor transducer type. It is widely used in laboratory instruments if the extraordinary precision of a capacitor transducer is not essential. Figure 15-8 shows the crystal transducer.

Certain crystals, such as quartz, Rochelle salt, and tourmaline, exhibit a piezoelectric effect. When they are stretched or compressed along a certain axis, known as the mechanical axis, an electric potential difference, which is proportional to the elastic strain produced in the crystal, appears along a perpendicular axis. The crystal transducer is able to transform vibrational energy into electrical energy in this way. Quartz is a superior material but is quite expensive. Rochelle salt melts at 65 degrees C and is adversely affected by high humidity. Therefore, some consideration must be given to the operating environment of a crystal transducer. Air pressure variations are transmitted to the crystal by mechanical coupling with a diaphragm and the emf is taken from electrodes attached to opposite faces. These electrodes may be plated or vaporized onto the crystal. The edges of the crystal are clamped in place at the corners.

Crystals are used for sound frequencies from a few Hertz to several mega Hertz.

Vibration pick-ups are commonly found on the home phonograph player. This particular device converts the sound recorded on the phonograph record to the electrical impulses which are amplified and fed to the systems's loud speakers.

The transducer involved frequently incorporates a crystal in much the same way as the crystal microphone. Pressure created by the movement of the needle as it follows the grooves cut in the record produces a corresponding voltage. Figure 15-9 shows a monaural pick-up.

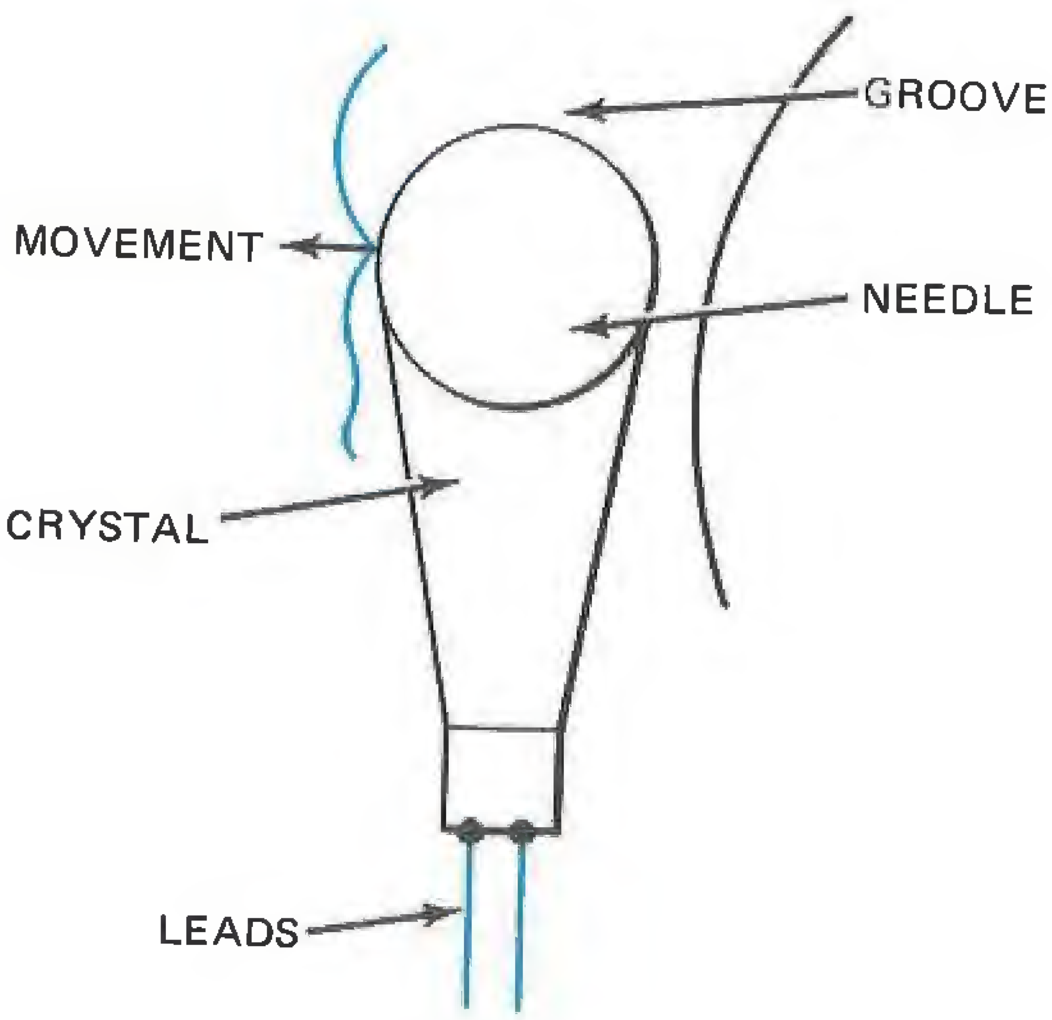
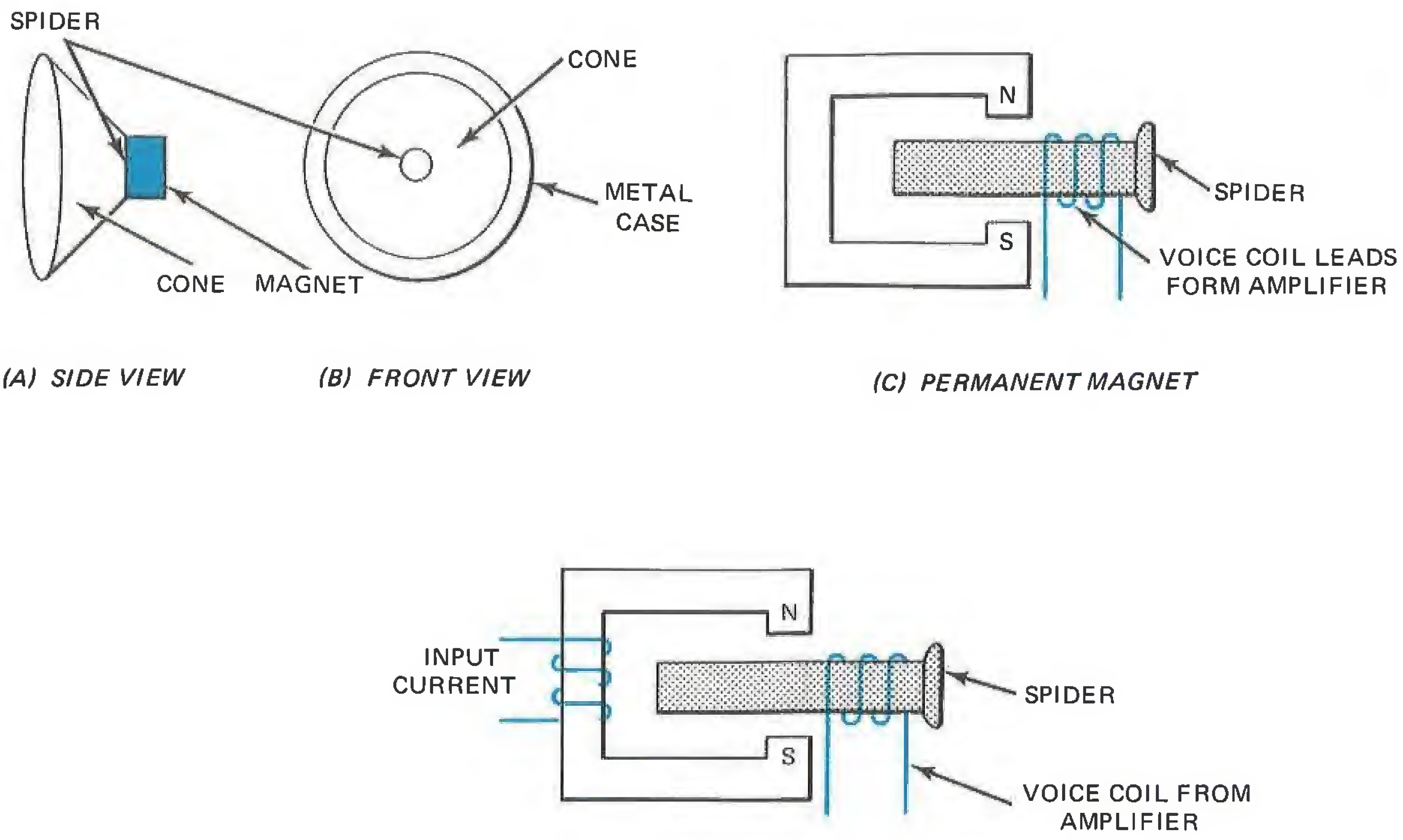


Fig. 15-9 Crystal Pick-Up used in Phonograph Players



(A) SIDE VIEW *(B) FRONT VIEW* *(C) PERMANENT MAGNET*

(D) ELECTROMAGNET

Fig. 15-10 Speaker Configurations

A loud speaker is a sound transducer which acts in the reverse way from a microphone. The most common types are the permanent magnet and the electromagnet ones shown in figure 15-10.

The permanent magnet speaker shown in figure 15-10C is essentially a movable coil that responds to the amplified current from the microphone or pick-up. The coil moves back and forth between the magnetic poles. The direction depends upon the current in the coil. The spider, a soft fabric, is connected to the coil and vibrates at the frequency of the coil movement. Attached to the spider is a cone which magnifies the vibrations and pushes the air away producing a sound.

An electromagnetic speaker operates much the same as a permanent magnet type. The only difference is that a current is passed through a coil of wire wrapped around the magnet which sets up the positive and negative poles of the magnet. When this is done, the voice coil acts the same as it did in the permanent magnet loud speaker.

The physical size of the speaker is important in the design of a sound system. Bodies that vibrate at high frequencies produce high, screeching sounds. These are described as high-pitched sounds. Bodies that vibrate slowly produce sounds of low pitch. For the low pitch sounds, a speaker with a large cone is best. For the high-pitched sounds, a speaker with a small cone is preferable.

MATERIALS

1 Oscilloscope, capable of reading 0.005 volts
1 Audio oscillator
1 Speaker, 4 in., 8Ω impedance
1 Speaker, 5 in. x 8 in. oval, 8Ω impedance
1 Transistor, Hep 232 or equivalent
1 DC power supply (0-40V)
1 Resistor, 4.7k, 1/2W
1 Resistor, 1.2k, 1/2W
1 Resistor, 18Ω, 2W
1 Capacitor, 1 μF, 10V
2 Speaker mounts
1 Resistor, 10k, 1/2W
1 Transformer, 100:3.2/8/16 ohms
1 Sheet semilog graph paper (three cycle)

PROCEDURE

1. Connect the circuit shown in figure 15-11.

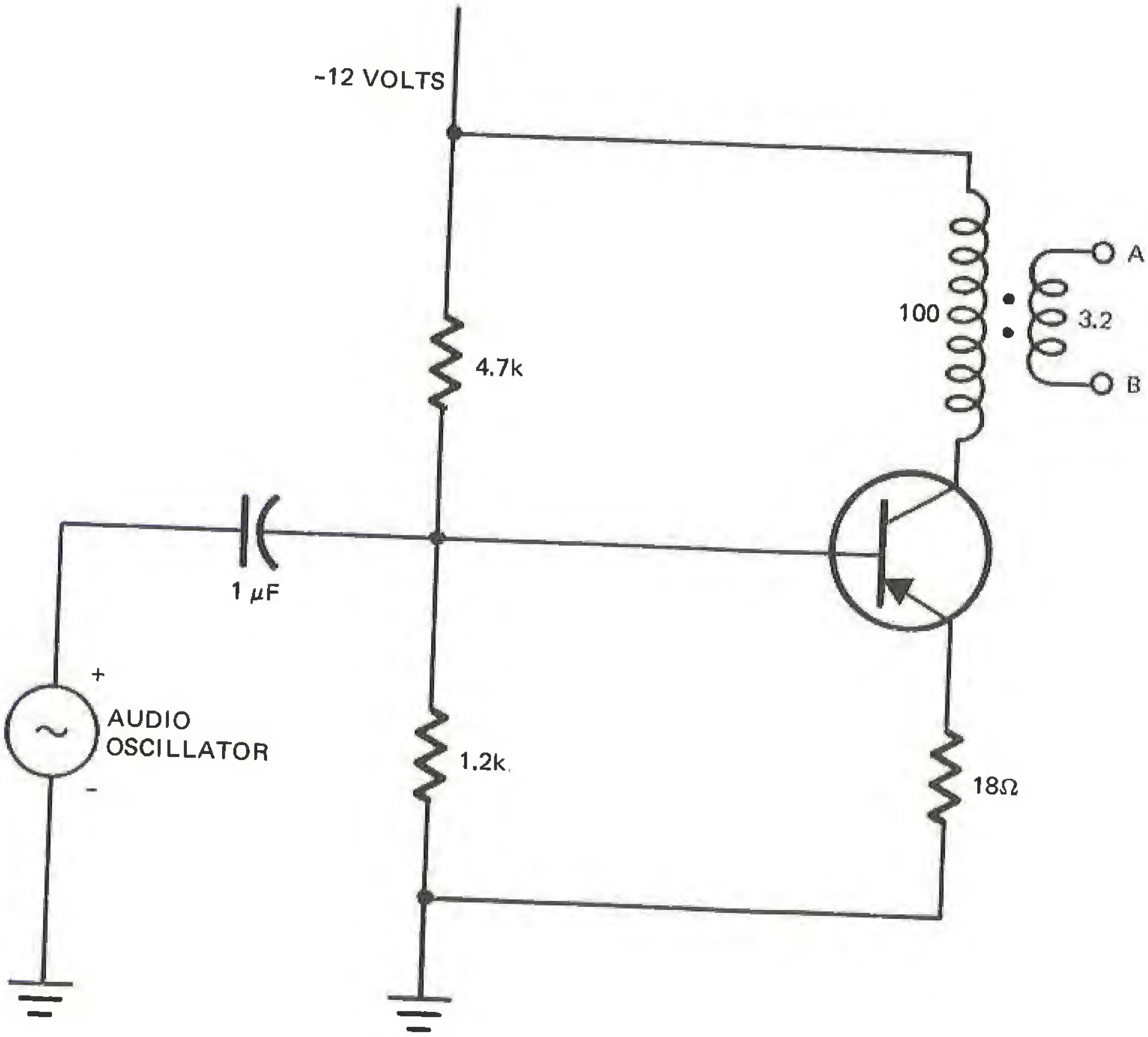


Fig. 15-11 Amplifier Circuit for Sound Transducer

2. At terminals A and B connect one of the speakers. Mount it so that it will not move.
3. Mount the second speaker two inches in front of the first one.
4. Put a 10k resistor in parallel with the second speaker. The apparatus should look like figure 15-12.

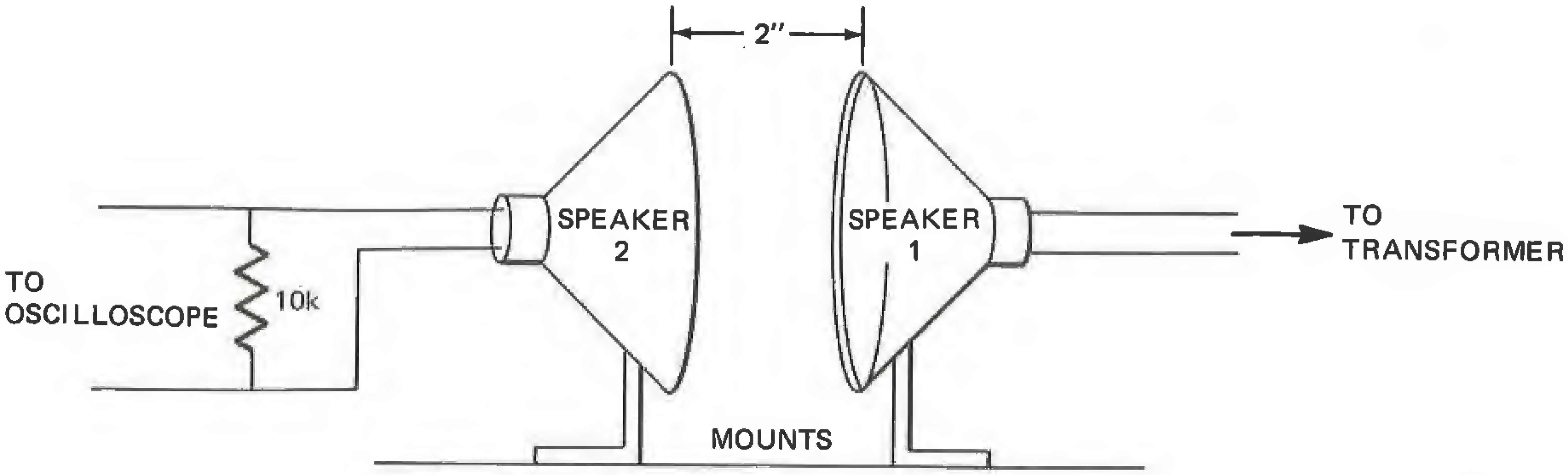


Fig. 15-12 Experimental Setup

5. With the frequency of the audio oscillator set at 30 Hertz, vary the amplitude until the input voltage to speaker one is one volt. **This voltage must be measured with the oscilloscope and adjusted for every frequency input.**
6. Measure the output voltage of speaker two. Record it in figure 15-14.
7. Change the frequency to 50 Hertz.
8. Readjust the input voltage.
9. Record the voltage output of speaker two.
10. Increase the frequency to 100 Hertz.
11. Repeat steps 8 and 9.
12. Repeat the measurement for frequencies of 200, 300, 400, 500, 800, 1000, 2k, 3k, 4k, 5k, 6k and 10k Hertz. Record all of the voltage outputs in figure 15-14.
13. Plot a graph of voltage output versus frequency on semi-log graph paper. Plot frequency on the logarithmic axis and voltage on the linear axis. At the resonant point, the curve may go off the paper. A typical curve for an inexpensive speaker should look somewhat like figure 15-13.

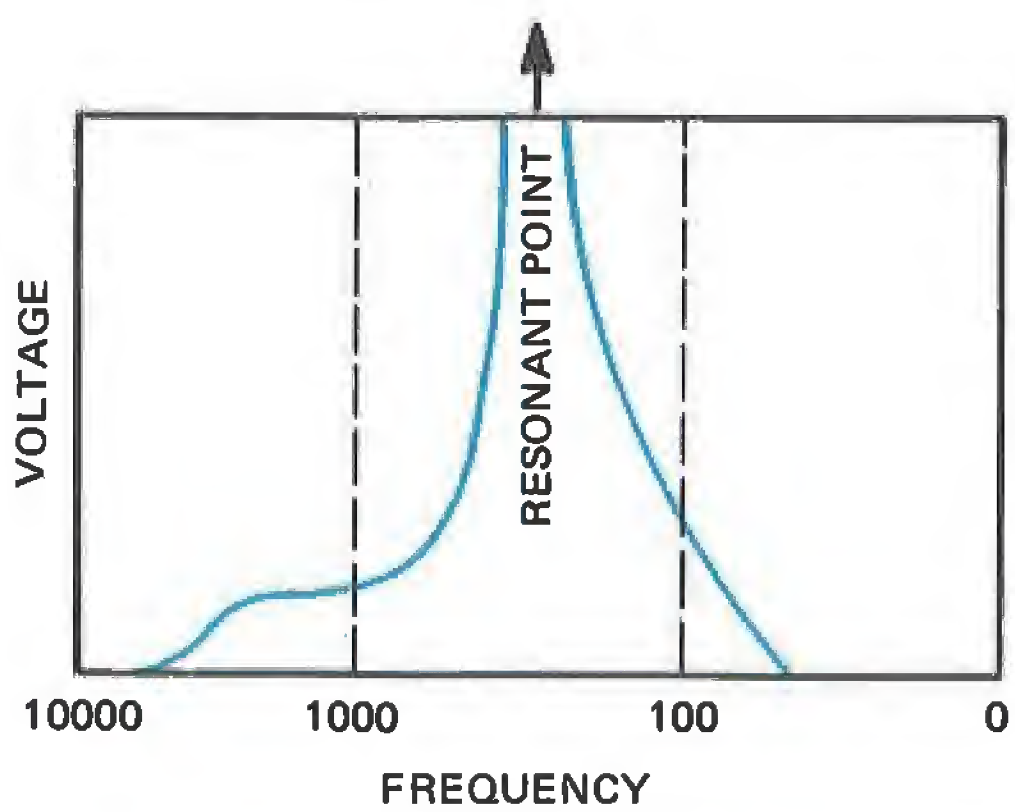


Fig. 15-13 A Typical Frequency – Voltage Curve for an Inexpensive Speaker

Frequency	Voltage One	Voltage Two
30	1	
50	1	
100	1	
200	1	
300	1	
400	1	
500	1	
800	1	
1000	1	
2k	1	
3k	1	
4k	1	
5k	1	
6k	1	
10k	1	

Fig. 15-14 Data Table of Frequency Versus Output Voltage for Speaker Two

ANALYSIS GUIDE. Explain the relationship of frequency versus output voltage for the sound transducer. Why was it important to readjust the input voltage to the first speaker for each frequency? Explain why this experiment is difficult to perform satisfactorily in a laboratory situation.

PROBLEMS

1. Using equation 15.1 compute the capacitance given n = 4, t = 8, A = 2, K = 1.6.
2. Compute the value of t in equation 15.1 given $C = 6 \times 10^{-6}$, n = 2, A = 4, K = 0.8.
3. Referring to the types of microphones listed in the discussion, which type would the pick-up used in this experiment fall into?

EXPERIMENT 1 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

Load (oz)	24	32	40	48	56	64	72
Resistance							

Fig. 1-9 The Data Table

Temp. (°F)	Room Temp	80	85	90	95	100
Resistance						

Fig. 1-11 Temperature-Resistance Table

EXPERIMENT 2 ______ Name ______

Date: ______ Class ______ Instructor ______

Time in 10 Sec Periods	Millivolts	Temp. °F
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		
110		
120		
130		
140		
150		
160		
170		
180		
190		

HEAT APPLIED

HEAT REMOVED

Time in 10 Sec Periods	Millivolts	Temp. °F

Fig. 2-17 Millivolt-Temperature Table for a Commercial Thermocouple

Fig. 2-18 Millivolt-Temperature Table for Lab Constructed Thermocouple

EXPERIMENT 3 Name ______________________

Date: ______________ Class __________ Instructor __________

15 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

20 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

25 psi	
Temp °F	Pressure
60	
62	
64	
66	
68	
70	
72	
74	
76	
78	
80	

Pressure Versus Temperature Indicator

Pressure	Relay On	Relay Off	Δ Pressure
15			
20			
25			

Relay Response

Temp	Pressure
75	
80	
85	
90	
95	

Pressure Versus Actual Temperature

Fig. 3-11 The Data Tables

EXPERIMENT 4

Name ____________________

Date: ____________________ Class __________ Instructor ____________

w	h	PE	E_1	E_2	E_3	E_{ave}
	1 in.					
	1-1/2 in.					
	2 in.					
	2-1/2 in.					
	3 in.					
	3-1/2 in.					
	4 in.					

Fig. 4-6 The Data Table

EXPERIMENT 5

Date: ______________________ Name ______________________

Class ____________ Instructor ______________________

	For Steel				For Aluminum			
Weight	0				0			
Resistance								
ΔR					0			
Strain $\frac{\Delta L}{L}$ Micro in/inch					0			
Stress (psi)					0			

Fig. 5-7 The Data Table

EXPERIMENT 6

Name ______________________

Date: ______________ Class __________ Instructor ______________

		2 kHz	4 kHz	6 kHz	8 kHz	10 kHz
0 in.	Voltage Current					
1/4 in.	Voltage Current					
1/2 in.	Voltage Current					
3/4 in.	Voltage Current					
1 in.	Voltage Current					

Force	0 oz	8 oz	16 oz	24 oz	32 oz	40 oz	48 oz	50 oz	64 oz
Voltage									

Fig. 6-10 The Data Tables

EXPERIMENT 7

Date: ______________

Name ______________

Class ______________ Instructor ______________

EXPERIMENT 8

Name ______________________

Date: ______________________

Class ____________ Instructor ____________

EXPERIMENT 9 Name ______________________

Date: ______________________ Class ____________ Instructor ______________

Liquid	Specific Gravity	Voltage
Distilled Water		
Tap Water		
Benzene		
Methanol		
Acetone		

Fig. 9-10 Data Table of Voltage Versus Specific Gravity

EXPERIMENT 10 ______ Name ______

Date: ______ Class ______ Instructor ______

Amount of Fluid	RPM	Time	Rev./Gal
1 Gallon	700		
1 Gallon	1000		
1 Gallon	1500		
Average Rev./Gal.			

Fig. 10-14 Data Table for Revolutions per Gallon

RPM	Voltage Output	Gal./Min.
500		
1000		
1500		
2000		

Fig. 10-15 Data Table of Flow Rate Versus Voltage Output of Generator

EXPERIMENT 11 Name ______________________

Date: ______________________ Class ____________ Instructor ______________

Depth inches	Voltage			
	Trial 1	Trial 2	Trial 3	Average
1	5	5	5	5
2				
3				
4				
5				
6				
7				
8				
9				
10				

Fig. 11-14 Data Table of Depth Versus Voltage Output

EXPERIMENT 12

Name ____________________

Date: ____________________ Class ____________ Instructor ____________

No. of Sheets	1	2	3
Voltage			

Fig. 12-9 Voltage Output Versus Obstruction

	Black Paper	Room Light	4 ft	3 ft	2 ft	1 ft	6 in.
Photovoltaic One							
Photovoltaic Two							
With 20Ω Resistor (Voltage)							
Current (mA)							
Power (mW)							
Photoconductor							

Fig. 12-10 Voltage Output Versus Illumination

EXPERIMENT 13 Name ______________________

Date: ______________________ Class ____________ Instructor ______________

Distance to Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-14 Data Table for Photovoltaic Cell Circuit

Distance from Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-15 Data Table for Photovoltaic-Photoconductive Cell Circuit

Distance from Photocell	6 in.	9 in.	12 in.	15 in.	18 in.	21 in.	24 in.
Voltage							

Fig. 13-16 Data Table for Two Photovoltaic Cells in Series

EXPERIMENT 14

Name ______________________

Date: ______________ Class __________ Instructor ______________

EXPERIMENT 15 Name ______________________

Date: ______________________ Class ____________ Instructor ____________

Frequency	Voltage One	Voltage Two
30	1	
50	1	
100	1	
200	1	
300	1	
400	1	
500	1	
800	1	
1000	1	
2k	1	
3k	1	
4k	1	
5k	1	
6k	1	
10k	1	

Fig. 15-14 Data Table of Frequency Versus Output Voltage for Speaker Two

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